Intelligent Power Quality Monitoring of Electrical Supply

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Intelligent Power Quality Monitoring of Electrical Supply

Presentation Outline

- Power Quality (PQ)
  - Definition and introduction
- PQ Events (Disturbances) Classification
- PQ Monitoring Equipment
- PQ Monitoring Techniques
- Intelligent PQ Monitoring
  - Disturbance Extraction
  - Event Categorization
  - Feature Extraction
  - Event Classification
  - Harmonics Extraction
  - Source Identification
- Summary

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What is a Power Quality Disturbance?

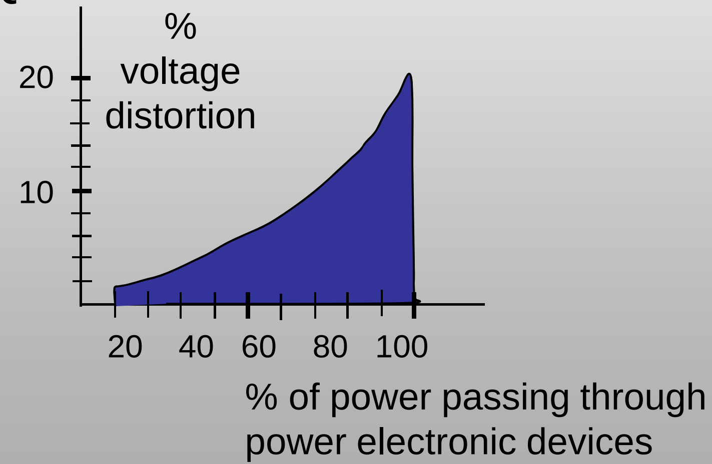
- Deviation (steady-state or transient) of voltage or current waveforms in an electrical supply system from a pure sinusoidal form of a specified magnitude and frequency.
- This deviation deform the a.c. supply voltage waveform and affect all loads connected to the supply point (Point of Common Coupling).

So what?

  – This “non-ideal condition” create problems for customers’ equipment as well as supply network, depending on the components that cause the disturbance/distortion, their magnitude, frequency and duration.
  – Signal distortion is normally associated with relatively high frequency components, which flow in the system, at relatively great distance from their point of origin.

Power Quality Disturbances

- **Why now?**
  - Modern electrical equipment are sensitive to PQ disturbances e.g. microprocessor-based controllers, power electronic devices such as SMPS, variable speed drives, etc.
  - Modern equipment (same equipment!) largely employ power electronic switching devices and hence have become the major source of degradation of PQ.
  - Use of equipment that employ power electronics is continuously increasing.
    - About £20 billion of power electronic products installed annually



World wide Trend in products that employ PE devices

Power Quality Monitoring

- **Why Intelligent?**
  - Power networks are becoming more complex and active (Smart Grids)
  - Power Quality events cover a wide range of disturbances which continuously occur in different parts of power networks.
  - These events vary in their magnitude, time-scale, features, but may leave similar effects on the grid.
  - They could be of a transient or intermittent nature with very short time scale (less than 1 ms).
  - They can be very difficult to capture.

Power Quality Events

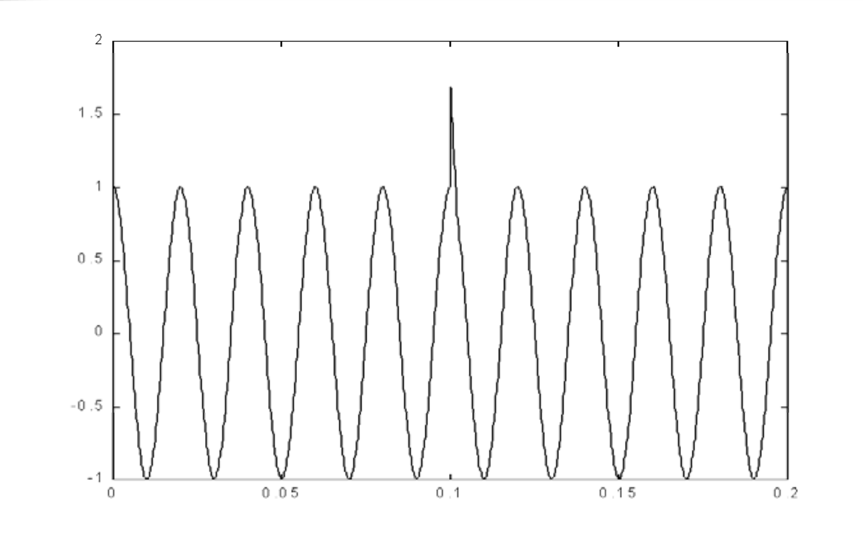
- Steady-State Events
  - Long term abnormalities in the voltage/current waveform.
  - Information are best presented as a trend of disturbance level over a period of time (relatively long), and then analysed using statistical methods.
  - e.g. voltage imbalance, waveform distortions and harmonics.
- Transition Events
  - Sudden abnormalities of relatively short duration, occurring in the voltage/current waveform.
  - Normally detected when the instantaneous value of the voltage/current exceeds a certain threshold.
  - They occur between two steady-state events or superimposed on a steady-state event.
  - e.g. fast transients, short duration variation in frequency or voltage (e.g. voltage sag).

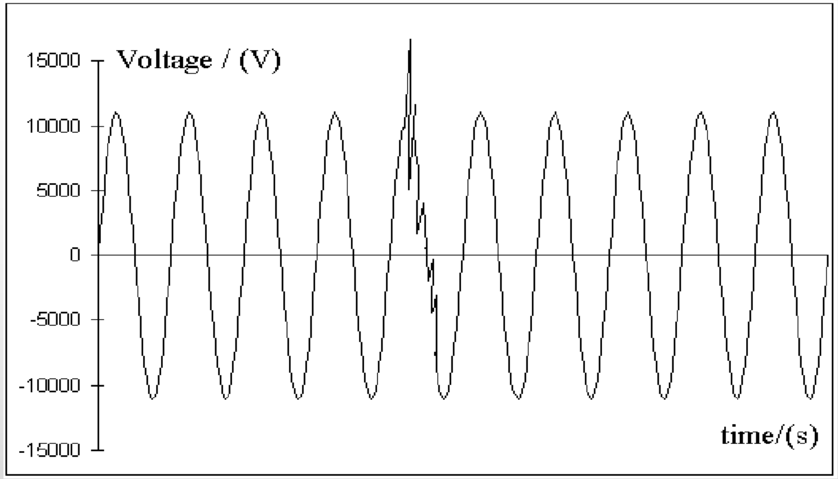
Power Quality Disturbances (Events)

Disturbance Type			Typical Duration	Typical Voltage Magnitude
Transients	Impulsive	Nanosecond	< 50 ns	
		Micro second	50 ns~1 ms	
		Millisecond	> 1 ms	
	Oscillatory	Low freq.	0.3~50 ms	0 ~ 4 pu
		Medium freq.	20 μs	0 ~ 8 pu
		High freq.	5 μs	0 ~ 4 pu
Short Duration Variation	Sag	Instantaneous	0.5~30 cycle	0.1~ 0.9 pu
		Momentary	30 cycl.~3 s	0.1~ 0.9 pu
		Temporary	3s ~1 min	0.1~ 0.9 pu
	Swell	Instantaneous	0.5~30 cycl.	1.1~1.8 pu
		Momentary	30 cycl.~3 s	1.1~1.4 pu
		Temporary	3 s ~ 1 min.	1.1~ 1.2 pu
	Interruption	Momentary	0.5 cycl.~3 s	< 0.1 pu
		Temporary	3 s ~ 1 min.	< 0.1 pu
Long Duration Variation	Sustained Interruption		> 1 min.	0.0 pu
	Under Voltages		> 1 min.	0.8~ 0.9 pu
	Over Voltages		> 1 min	1.1~ 1.2 pu
Voltage Imbalance	Magnitude Imbalance		Steady state	
	Phase Imbalance		Steady state	
Waveform Distortions	DC Offset		Steady state	0 ~ 0.1%
	Harmonics		Steady state	0 ~ 20%
	Interharmonics		Steady state	0 ~ 2%
	Notching		Steady state	
	Noise		Steady state	0 ~ 1%
Voltage Flicker			Intermittent	0.1 ~ 7%
Power Frequency Variations			< 10 s	.95~1.05 pu

Based on
IEEE Standards
1159-1995

Transient Events





Impulsive Transient

Unidirectional polarity

Nanosecond (<50ns)

Microsecond (50ns-1ms)

Millisecond (>1ms)

Oscillatory Transient

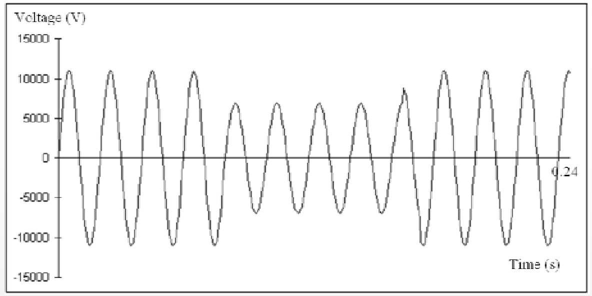
Change its polarity rapidly

Low frequency (20Hz-3.3 kHz)

Medium frequency (~50 kHz)

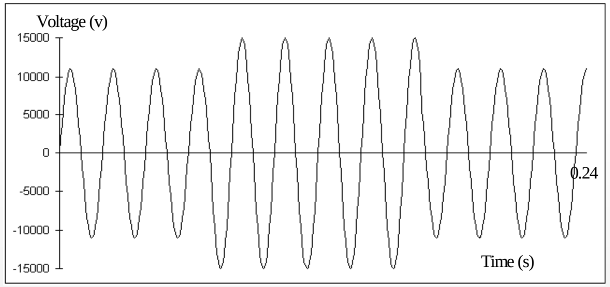
High frequency (~200 kHz)

Short-Duration Variation



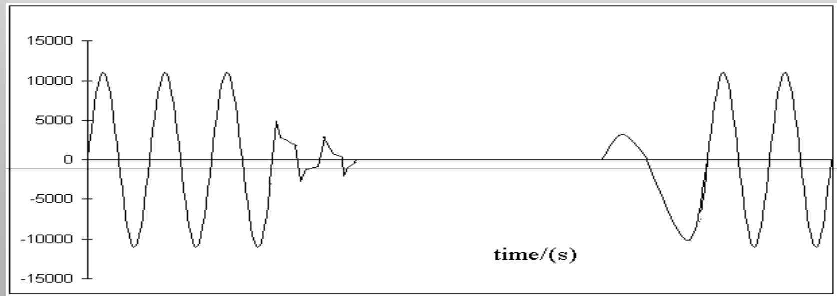
Sag

Decrease in the voltage level to 0.1 - 0.9 p.u.
Instantaneous (0.5-30 cycles)
Momentary (30 cycles – 3s)
Temporary (3s – 1 min)



Swell

A surge in the voltage level
Instantaneous (1.1-1.8 pu for 0.5-30 cycles)
Momentary (1.1- 1.4 pu for 30 cycles – 3s)
Temporary (1.1-1.2 pu for 3s – 1 min)



Interruption

Supply voltage falls below 0.1 p.u.
Momentary (0.5 cycle – 3s), Temporary (3s – 1 min)

Long-Duration Variation

Duration is more than one minute

Sustained supply interruption

A complete loss of supply

Under-voltage

A sustained decrease of supply voltage in the range 0.8~0.9 p.u.

Over-voltage

A sustained increase in supply voltage in the range of 1.1~1.2 p.u.

Voltage Imbalance

Usually this is a steady-state condition.

Voltage magnitude imbalance

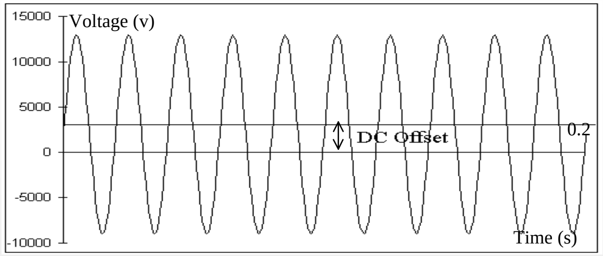
This is the ratio of negative or zero sequence component to the positive sequence component.

Voltage phase imbalance

A deviation from the normal 120^o phase angle difference between the voltages of the three phases

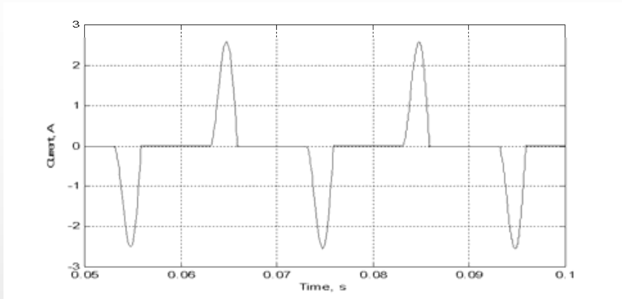
Waveform Distortion

A steady-state deviation that deform the sinusoidal waveform



D.C. Offset

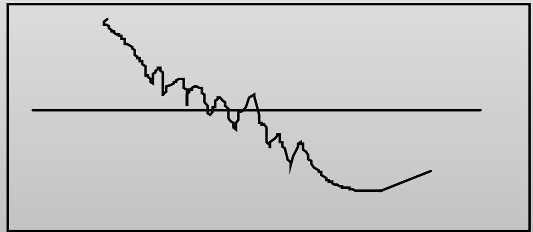
Typical value <0.1 %



Harmonics

Periodic waveforms that have integer multiple of the fundamental frequency.

Typical value <20 %)



Notching

A periodic voltage disturbance

Interharmonics

Periodic waveforms which are not integer multiple of the fundamental frequency.

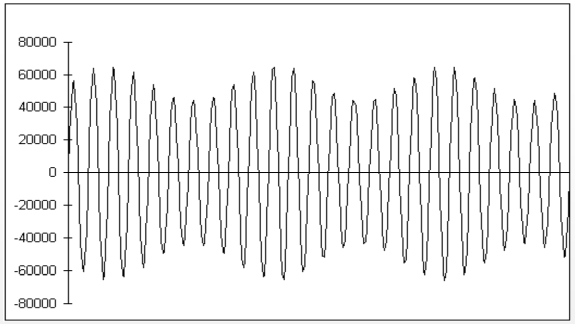
Typical value <2 %

Noise

A non-periodic distortion of the sinusoidal waveform

Typical value <0.1 %

Voltage Flicker (Voltage Modulation)



An intermittent series of systematic voltage fluctuations

Typical value 0.1-7%

Typical modulation frequency 1-10 Hz

Power Frequency Variations

A systematic fluctuations in the supply frequency (due to change in system dynamic balance) lasting for less than 10 sec.

Typical value 0.95-1.05 p.u.

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Electro Magnetic Compatibility (EMC)

EMC refers to equipment compliance with the national standards with regard to:

- The conducted and transmitted distortion generated by the equipment and
- The equipment susceptibility to the distortion or electromagnetic field caused by the supply system.

Electro Magnetic Interference (EMI)

EMI refers to the electromagnetic interference which affects the operation of equipment.

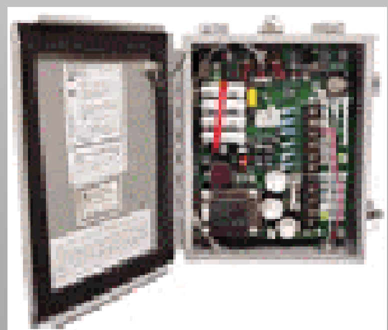
PQ Monitoring Equipment

- Handheld
  - Mainly single phase
  - Voltage and current measurement
  - On-the-spot analysis
  - Specifications vary, but useful for initial investigation

- Portable
  - For monitoring and analysis of a wide range of PQ problem, e.g. transients, harmonics, power, etc.
  - 3 phase voltage and current measurement
  - Capable of recording for long periods
  - Allows post recording computer analysis

PQ Monitoring Equipment

- Fixed PQ monitor/analyser
  - For long-term on-site monitoring
  - Capture a wide range of PQ problem
  - Can be linked to a PC for immediate analysis
  - Ability to communicate via the Internet (Ethernet-equipped instruments).
- Networked multipoint PQ monitors
  - For continual monitoring on a power network
  - Multiple Node Recorders and a Centralised monitoring & analysis unit
  - Allows a broad picture of PQ on a network
  - Ability to communicate



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PQ Monitoring Techniques

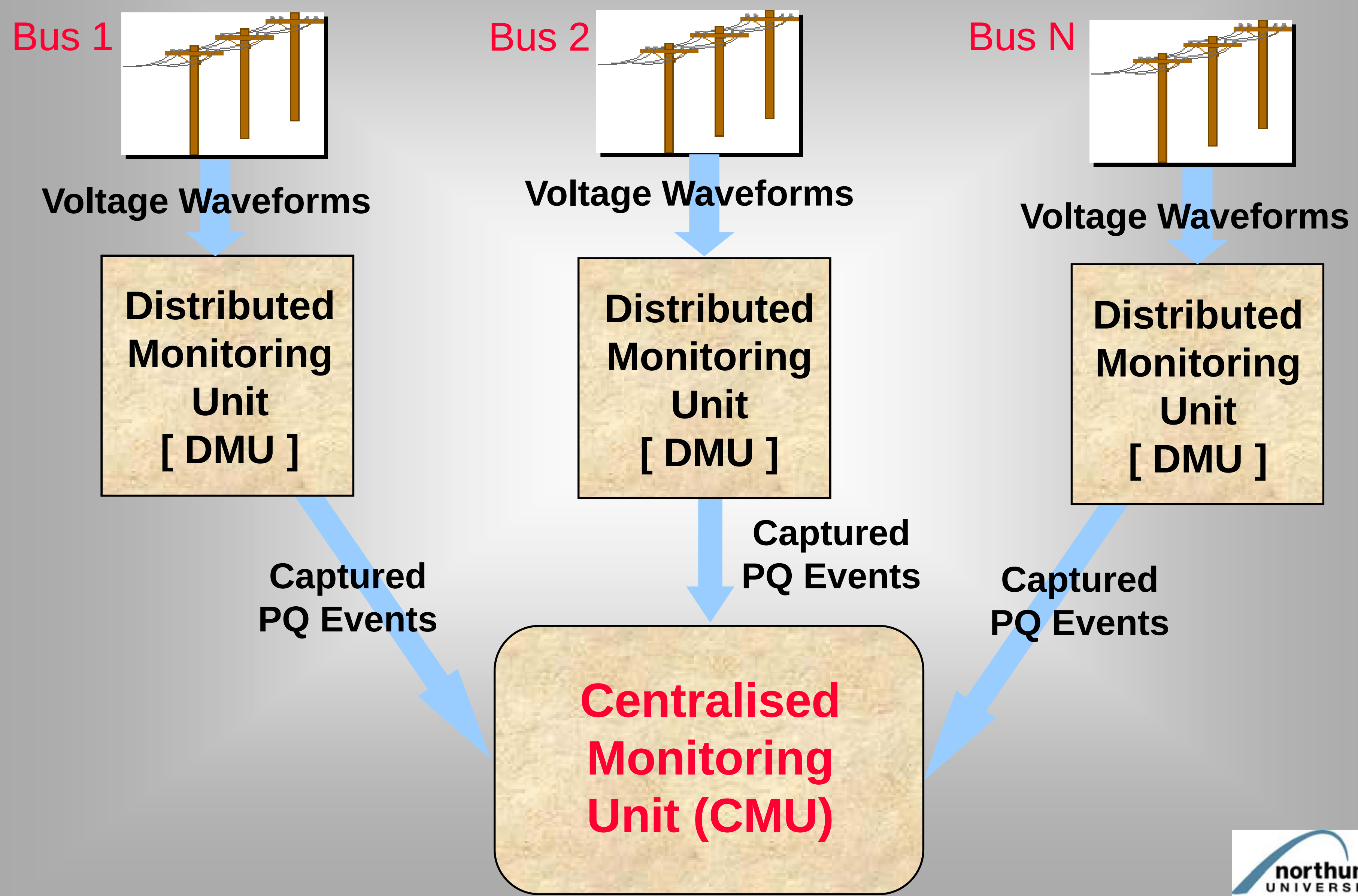
- Time Domain
  - Using filters or DSP techniques
  - Straightforward design, but inflexible, complex & response can be slow.
  - Does not provide much insight into the signal (e.g. frequency information of the signal is not directly observable)
- Time and/or Frequency Domain
  - Frequency analysis (e.g. FFT)
  - Time/frequency analysis (e.g. Wavelet Transform)
  - Good extraction capability for PQ analysis, flexible, but require large computational power. FFT response is limited to one cycle of the signal.
- Artificial Intelligence
  - Artificial Neural Networks (ANN)
  - Good extraction capability, flexible, fast response, adapt to changes in the system. Need appropriate training

An ideal PQ Monitoring System would be able to:

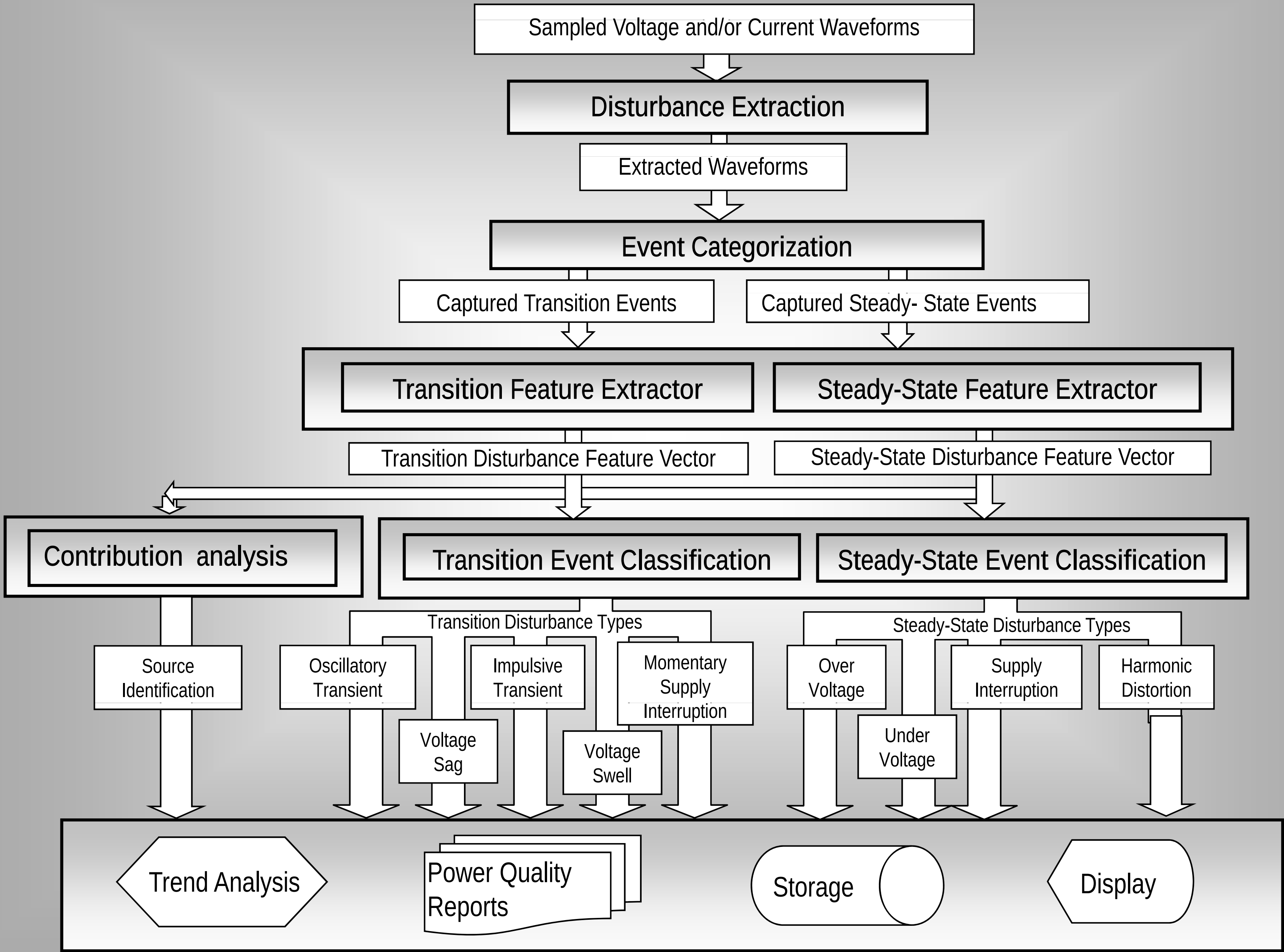
- Capture and extract disturbance waveform
- Categorize disturbance (steady-state or transient)
- Extract disturbance features and identify components
- Classify the disturbance (according to IEEE standards 1159)
- Trend analysis
- Contribution analysis and source identification

PQ Report and Advice

Networked Multipoint PQ Monitoring System

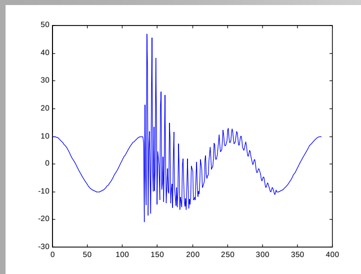


‘Intelligent’ PQ Monitoring System (IPQMS)



Disturbance Extraction

Identify the presence of a disturbance and extract its components



Voltage Waveform

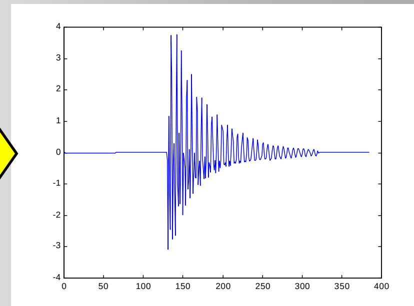
$$e(t) = v(t) - \frac{\mathrm{Re}(C)\cdot Vr(t) + \mathrm{Im}(C)\cdot Vr(t-\frac{T}{4})}{\| C \|}$$

$$r = \| \mathrm{C} \|$$

where,

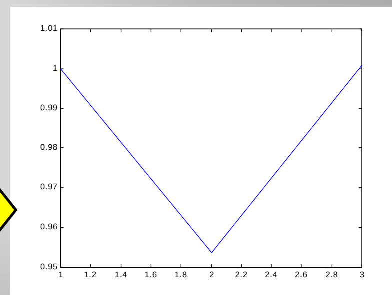
$$C = \int_0^T \left[v(t)\cdot Vr(t) + j\cdot v(t)\cdot Vr(t-\frac{T}{4}) \right]\cdot dt$$

e(t)



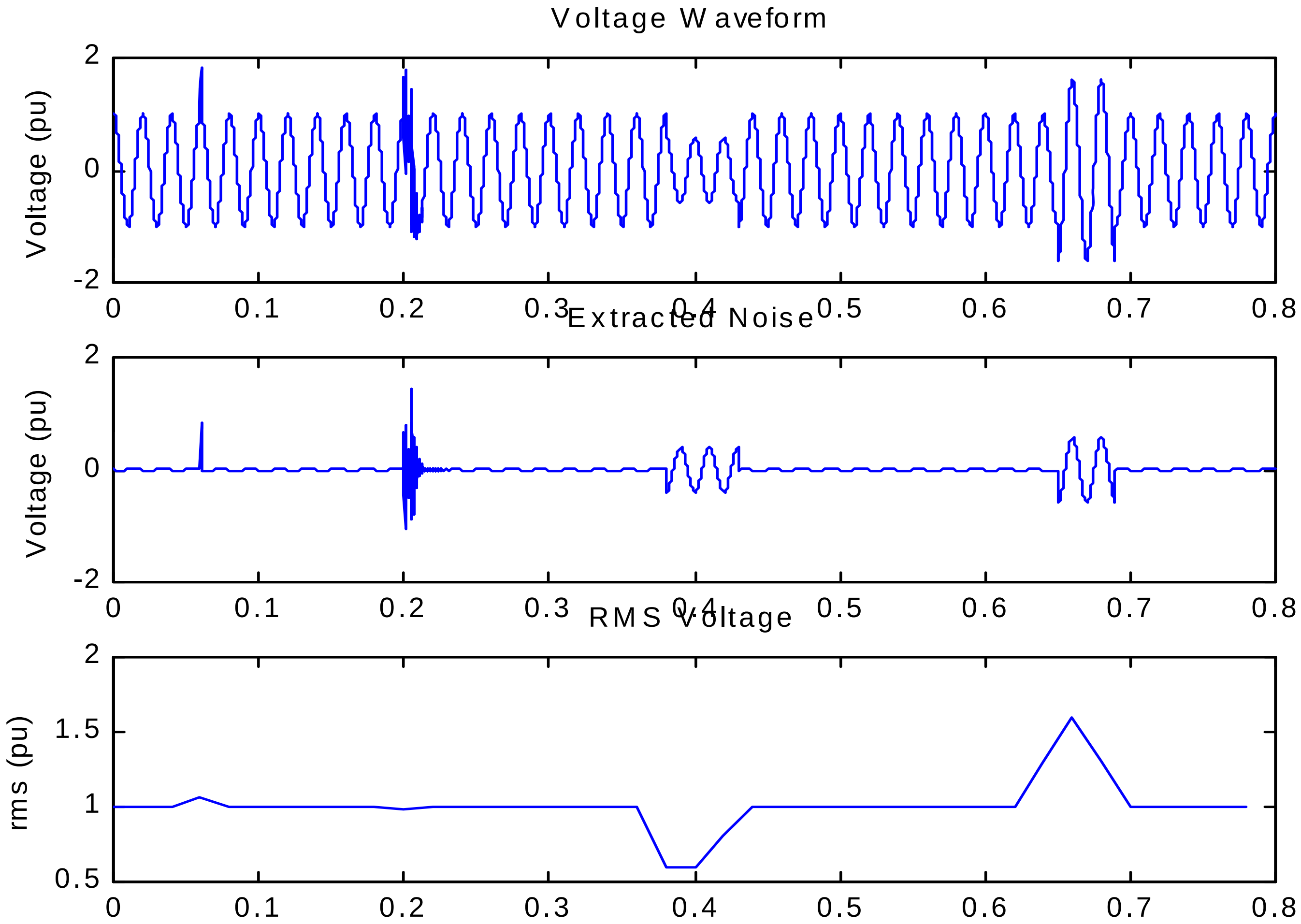
Extracted Disturbance

r

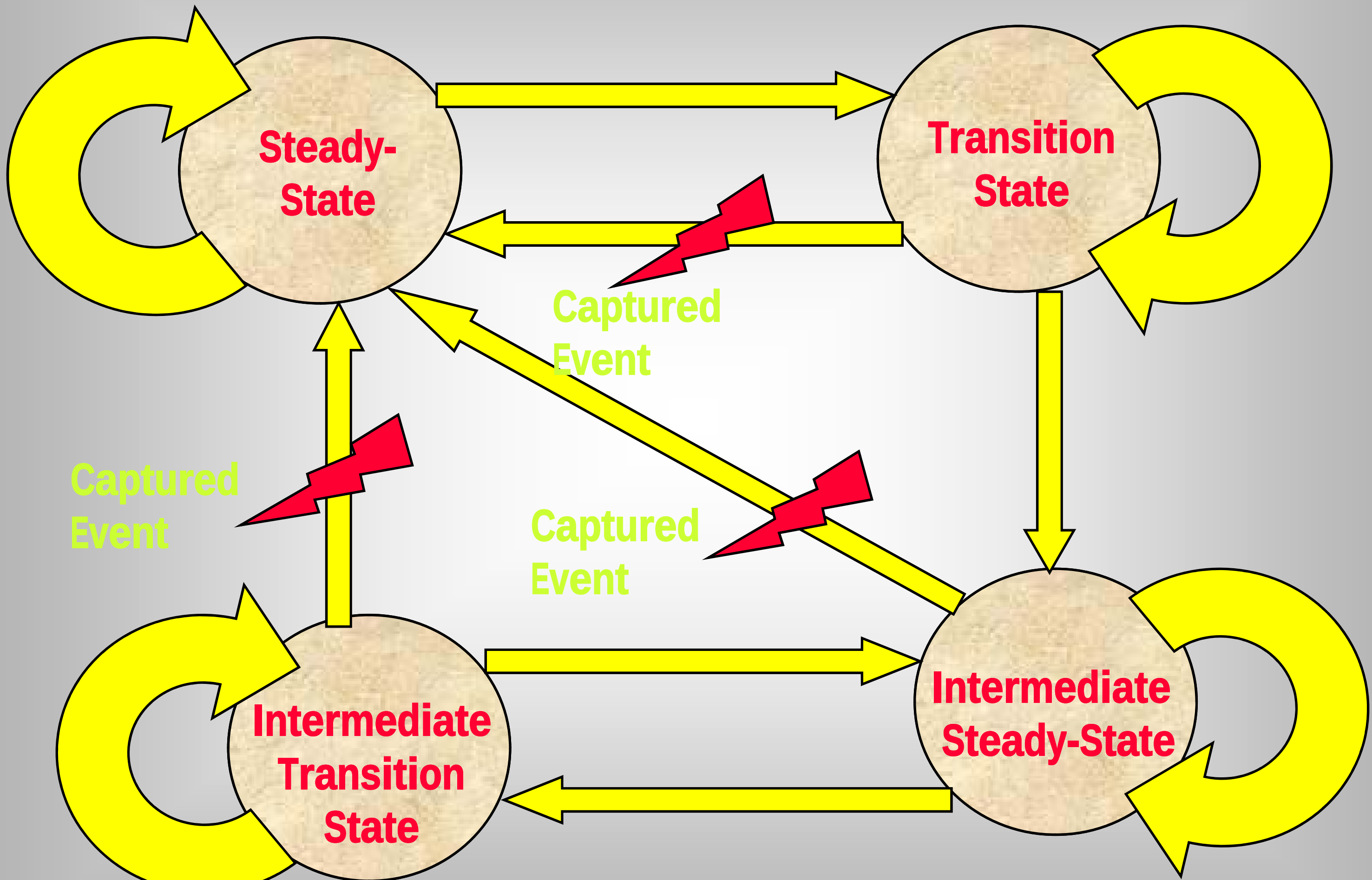


RMS Variation

Disturbance Extraction: Example

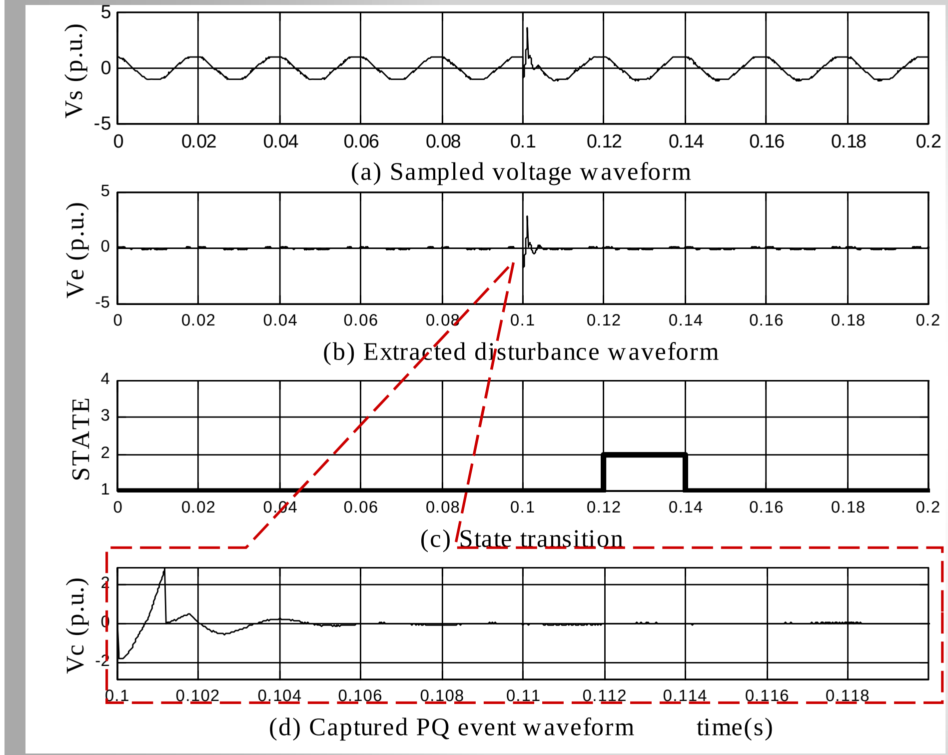


Event Categorization

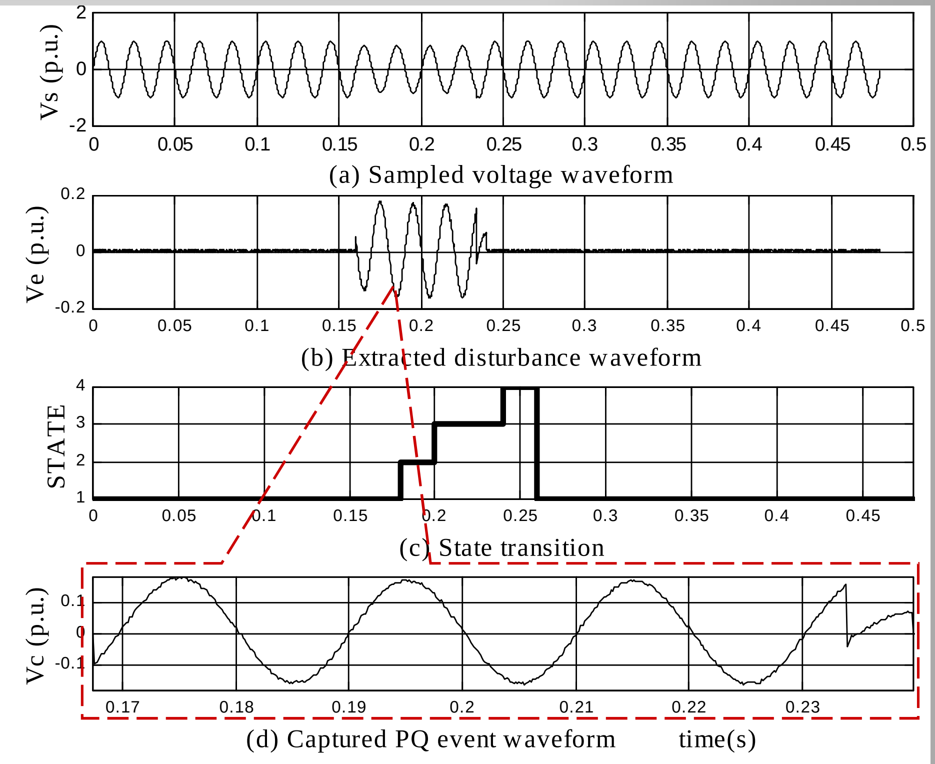


State Model

Event Categorization: Example

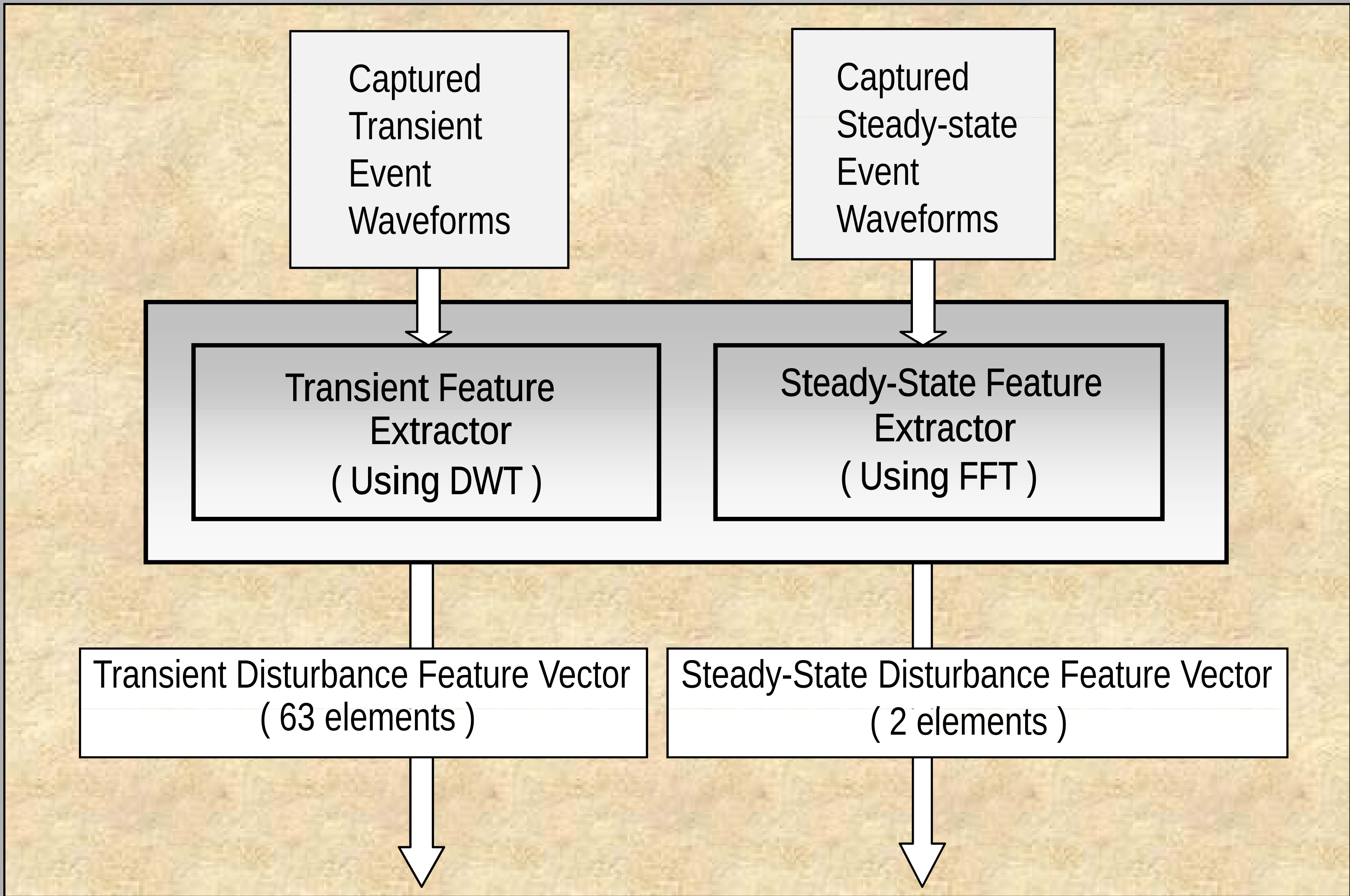


Identification of a voltage disturbance during a capacitor switching

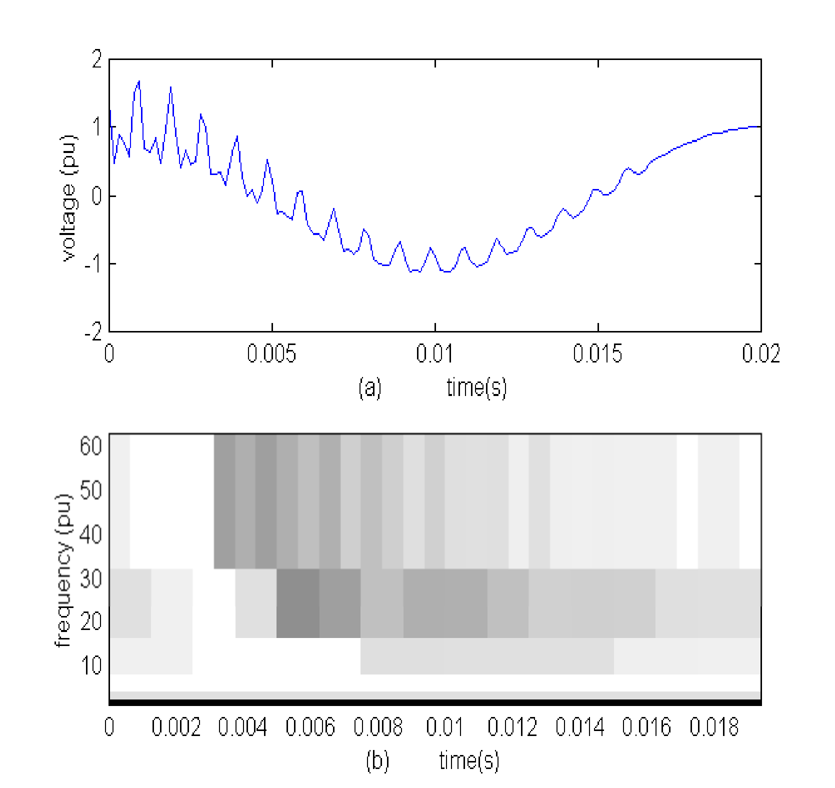


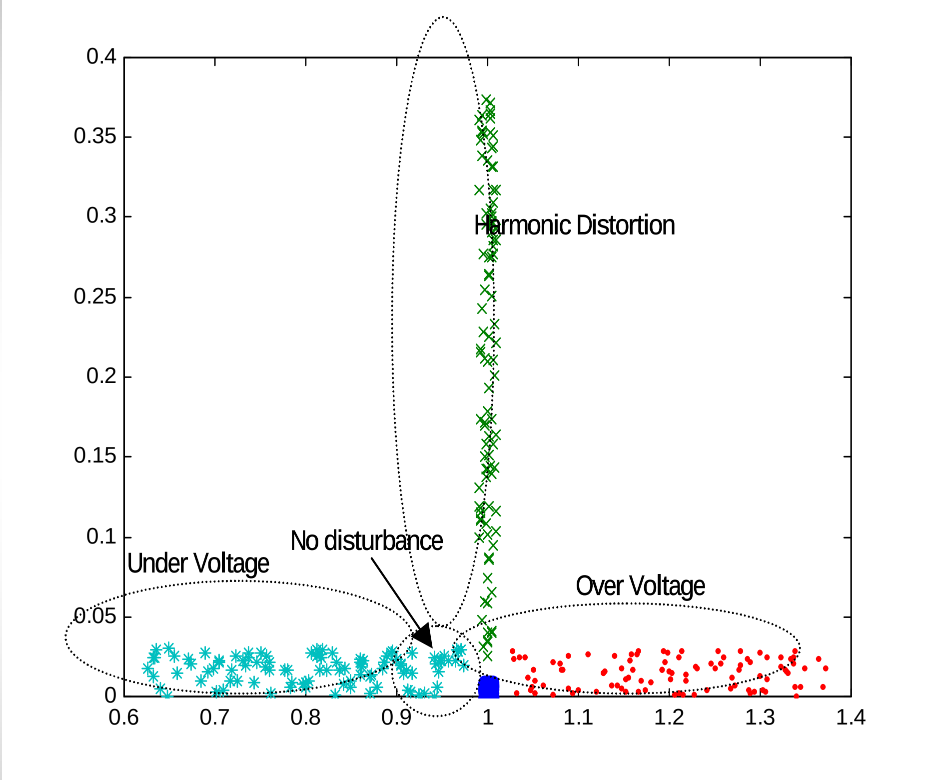
Identification of a voltage sag event generated by a remote network fault

Feature Extraction



Feature Extraction: Example

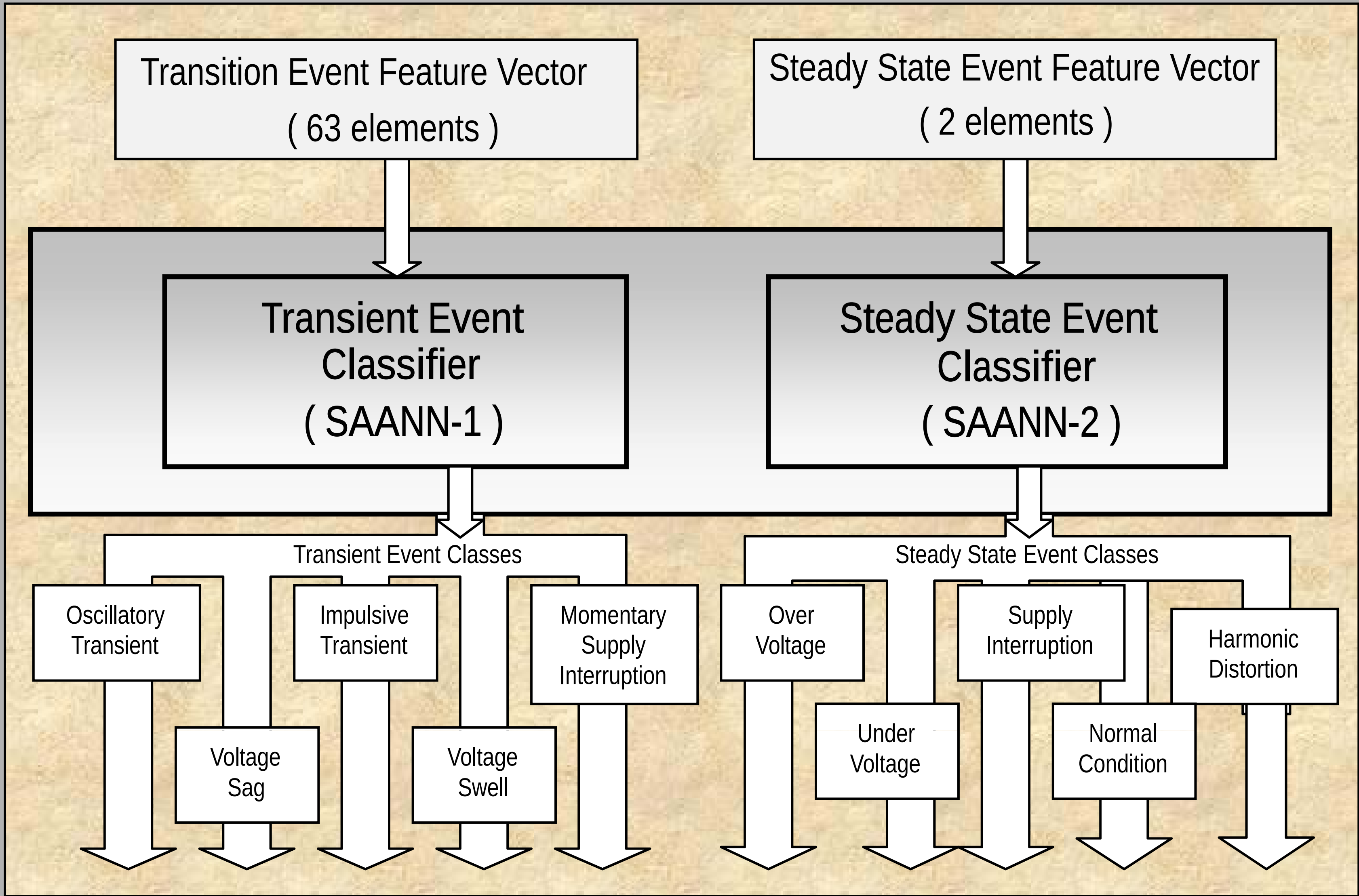




Oscillatory Transient

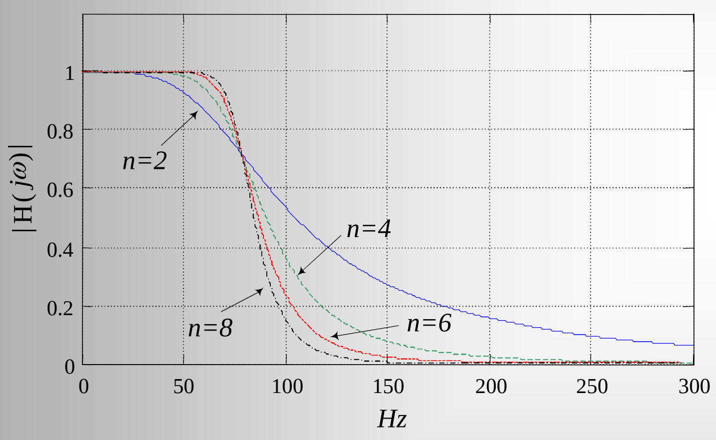
Steady-State Feature Space

Event Classification

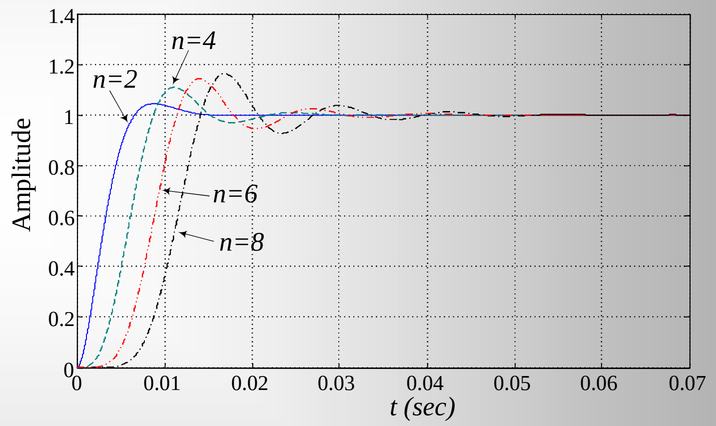


Time Domain Harmonic Extraction

Filter characteristic



Frequency Response

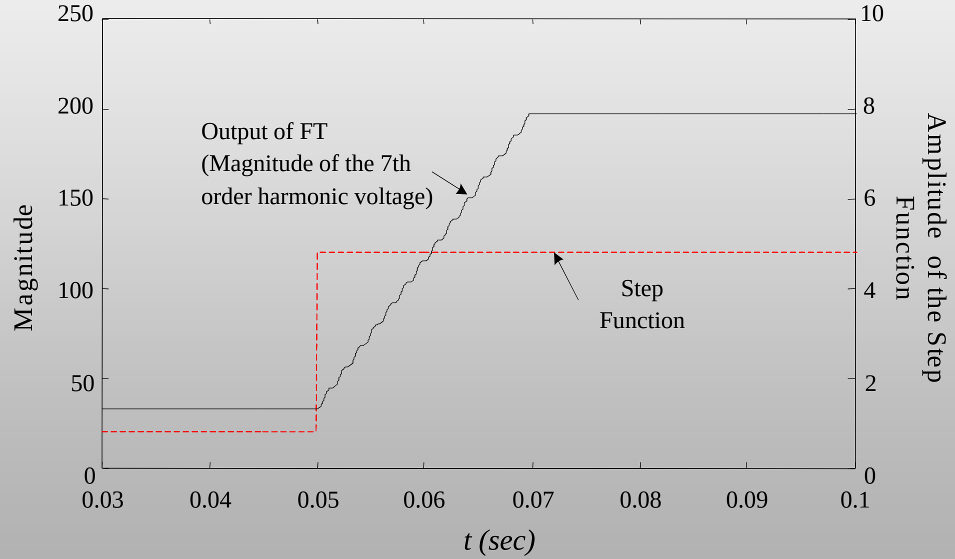


Time response

Frequency Domain Harmonics Extraction

Fourier Transform:

$$F(n\omega_0) = \frac{1}{T_0}\int_{t}^{t+T_0} f(t)\cdot e^{-jn\omega_0 t}\,dt$$



Fast Individual Harmonic Extraction (FIHE)

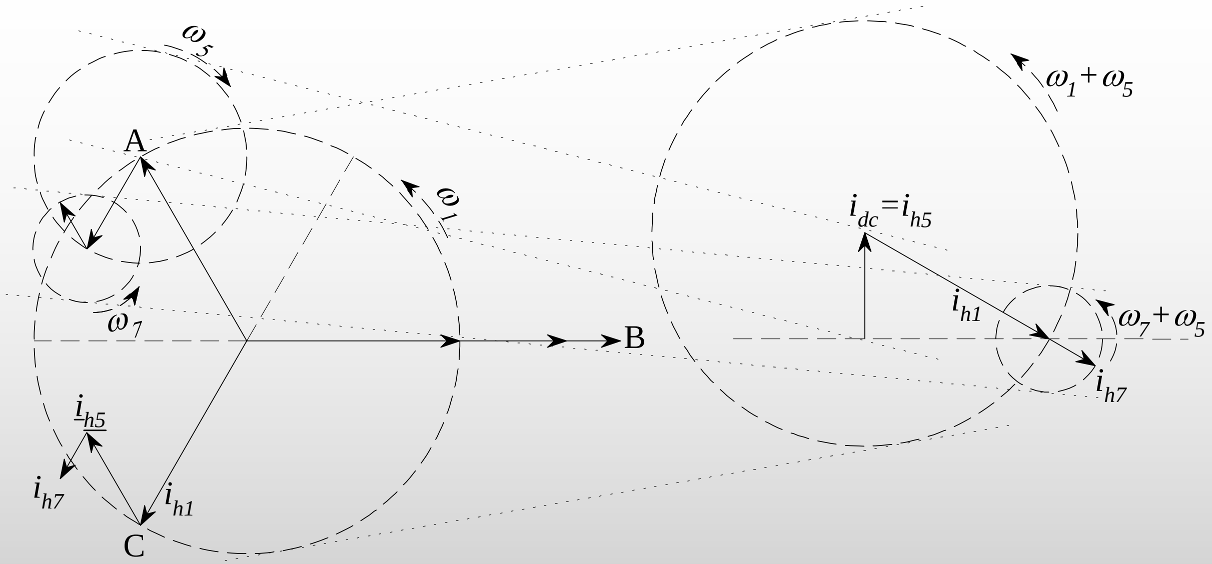
m^{th} order Harmonic Extraction

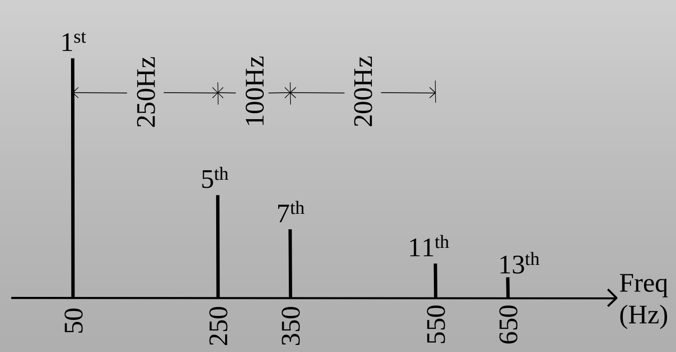
$$\beta_m(t) = \frac{4}{T_0}\int_{t}^{t+\frac{T_0}{6}} \sum_{\substack{n=2k-1\\ n\neq 3^k}}^{\infty} \left[\underbrace{\begin{bmatrix} \sin(m\omega_0 t) & \sin(m\omega_0 t - \frac{2m\pi}{3}) & \sin(m\omega_0 t + \frac{2m\pi}{3}) \\ \cos(m\omega_0 t) & \cos(m\omega_0 t - \frac{2m\pi}{3}) & \cos(m\omega_0 t + \frac{2m\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}}_{\alpha_{abc}(t)} \cdot \begin{bmatrix} M_n \sin(n\omega_0 t) \\ M_n \sin(n\omega_0 t - \frac{2n\pi}{3}) \\ M_n \sin(n\omega_0 t + \frac{2n\pi}{3}) \end{bmatrix} \right] dt$$

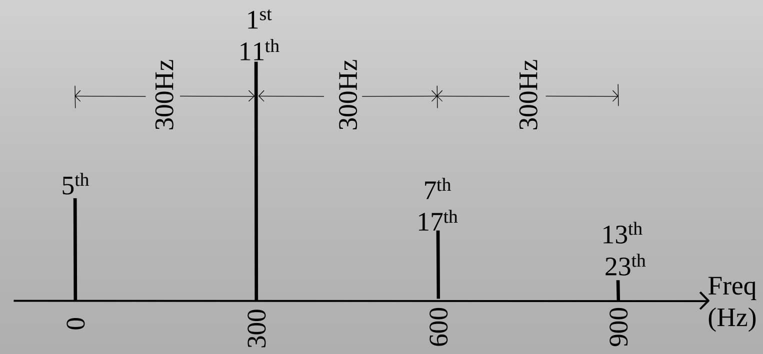
m^{th} order harmonic reconstruction

$$abc_m(t) = \frac{3}{2} \cdot \alpha_{abc}^{-1}(t) \cdot \beta_m(t)$$

Fast Individual Harmonic Extraction (FIHE)

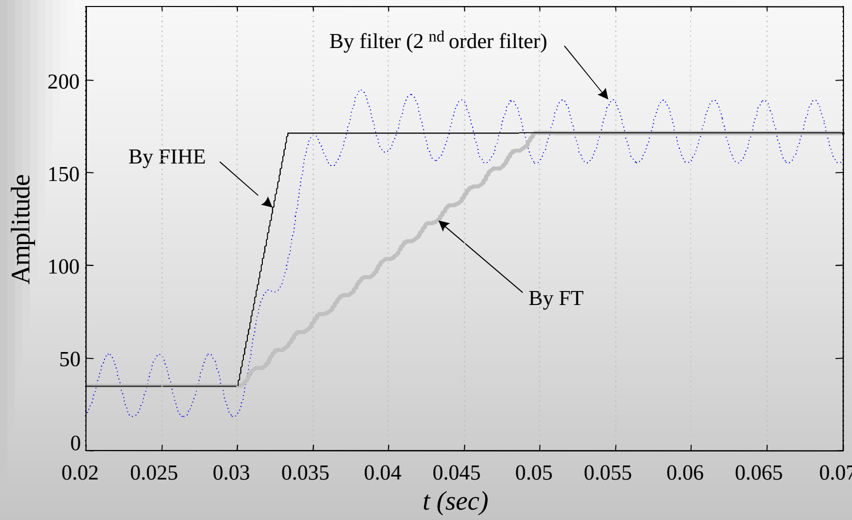




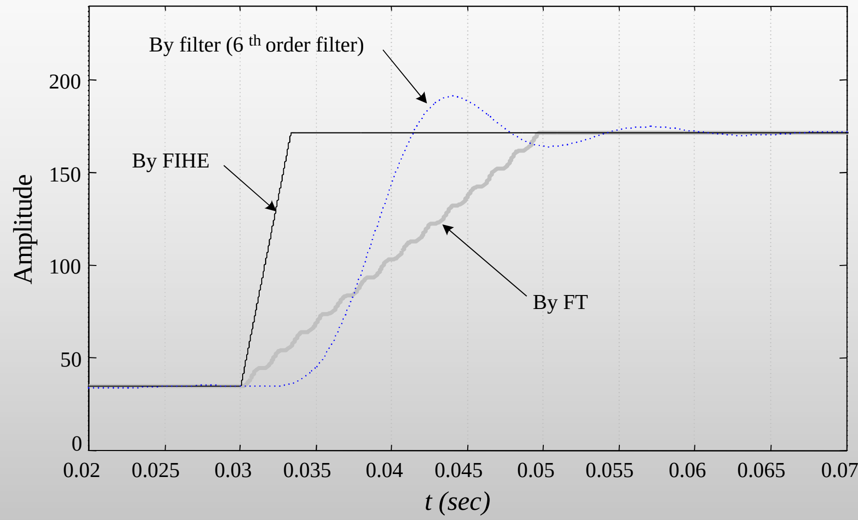


Performance Analysis

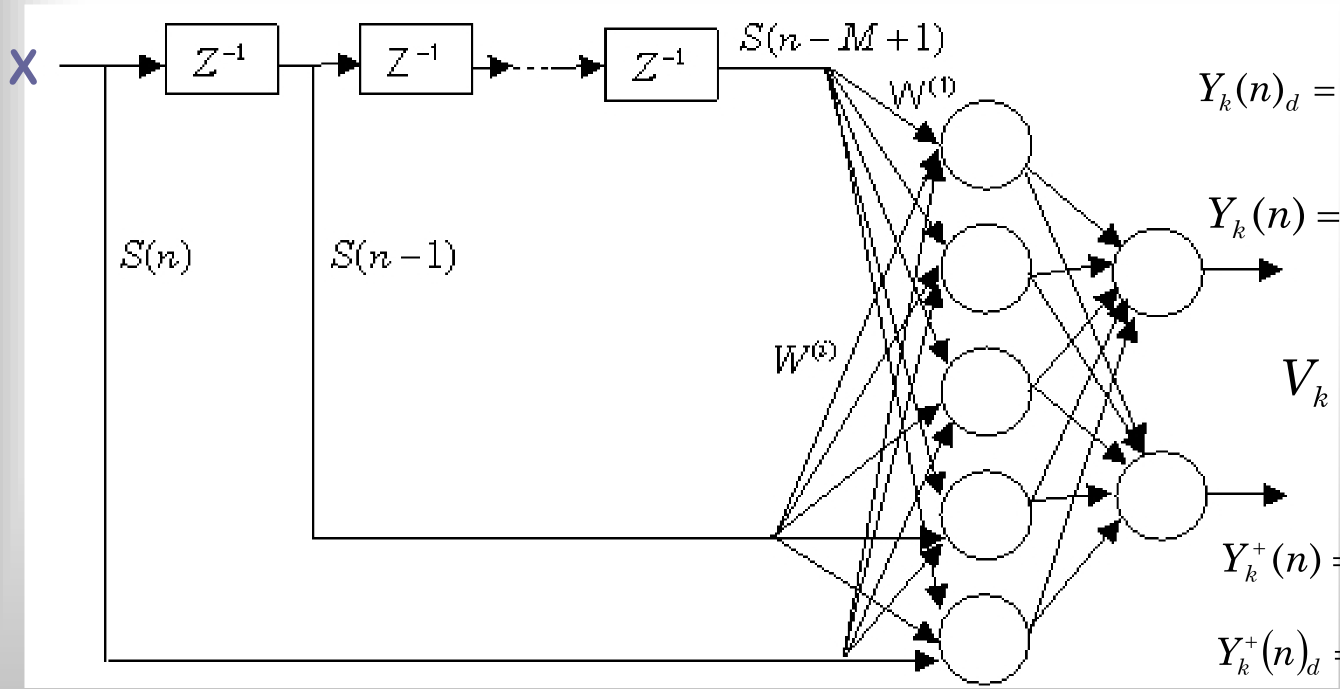
With low order filter



With higher order filter



Non-Recursive Technique using ANN



$$Y_k(n)_d = V_k \sin\left(\frac{k\omega n}{f_s} + \phi_k\right) \quad \text{Desired}$$

$$Y_k(n) = f(X, W) \quad \text{Actual}$$

$$V_k = \sqrt{Y_k(n)^2 + Y_k^+(n)^2}$$

$$Y_k^+(n) = f^+(X, W) \quad \text{Actual}$$

$$Y_k^+(n)_d = V_k \cos\left(\frac{k\omega n}{f_s} + \phi_k\right) \quad \text{Desired}$$

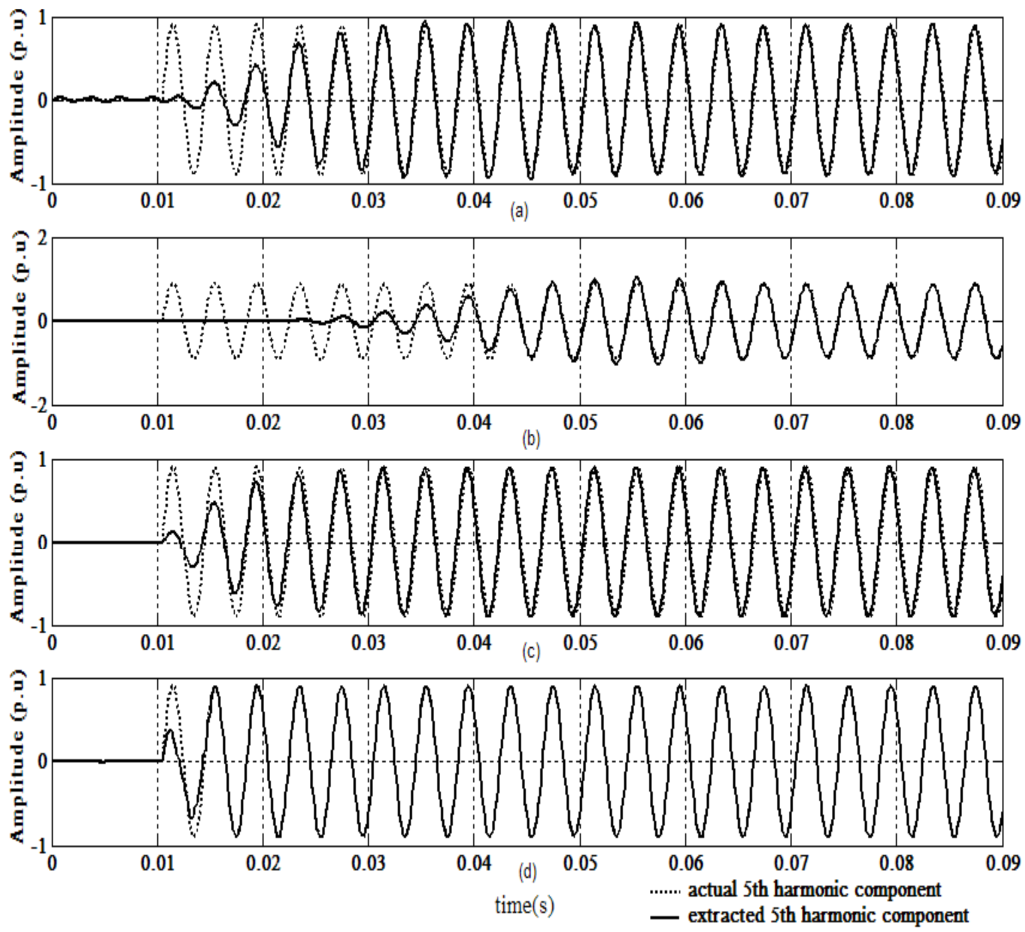
$$X = [S(n-M+1) \quad S(n-M) \quad \ldots \quad S(n-1) \quad S(n)]^T$$

Least Mean Square (LMS) algorithm used for training the ANN

$$W^{(i)}{}_{new} = W^{(i)}{}_{old} - \alpha \frac{\partial \varepsilon^2}{\partial W^{(i)}}$$

$$where \quad \varepsilon^2 = (Y_k(n)_d - Y_k(n))^2 + (Y_k{}^+(n)_d - Y_k{}^+(n))^2$$

Response to a step increase of 5^{th} harmonic component



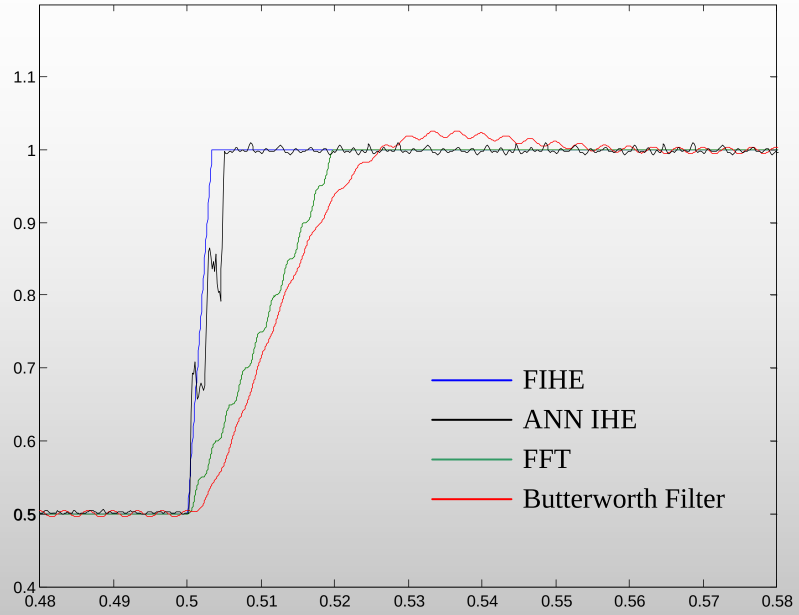
2^{nd} order filter

6^{th} order filter

Kalman Filter

ANN

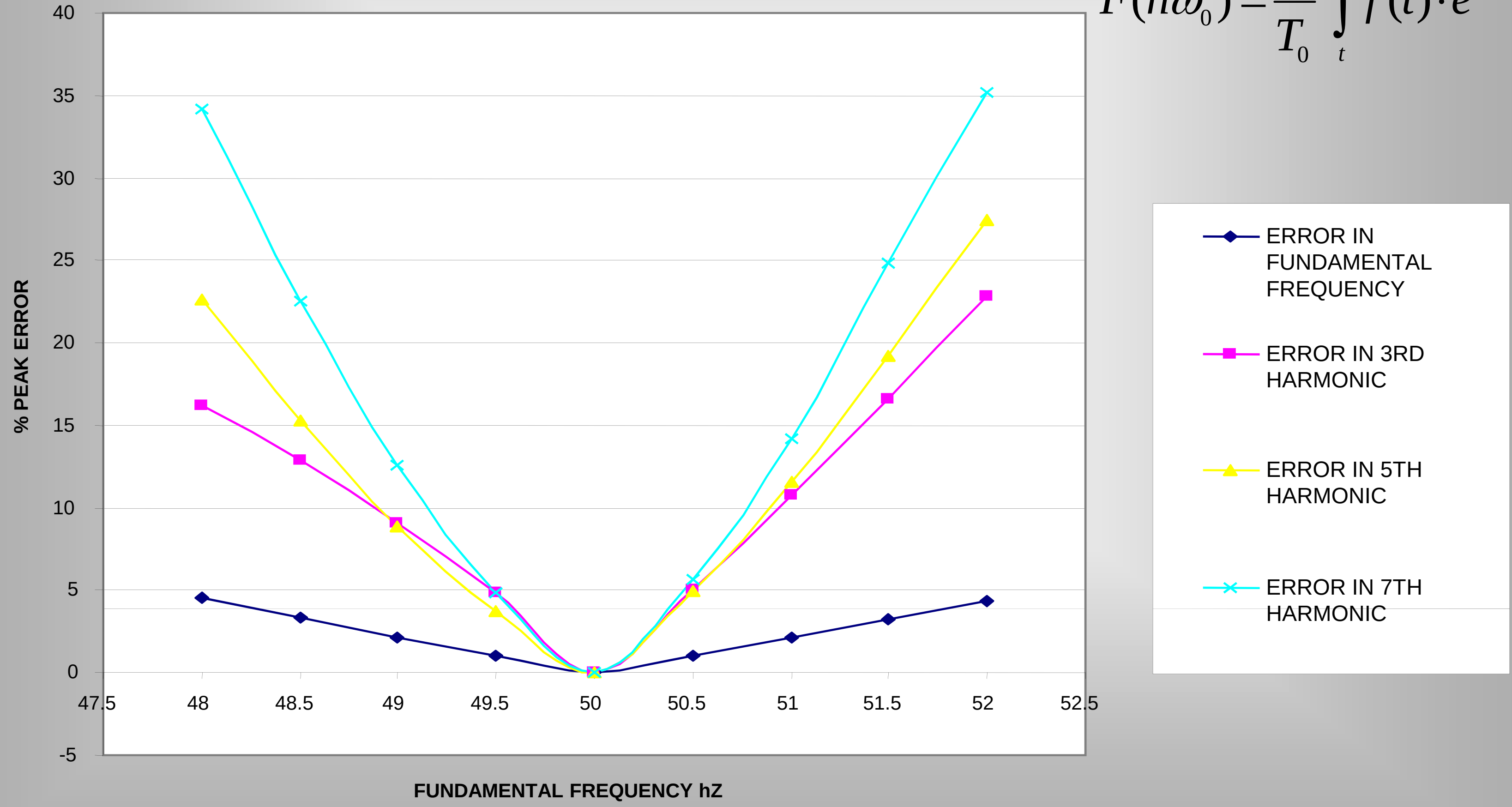
Performance Analysis



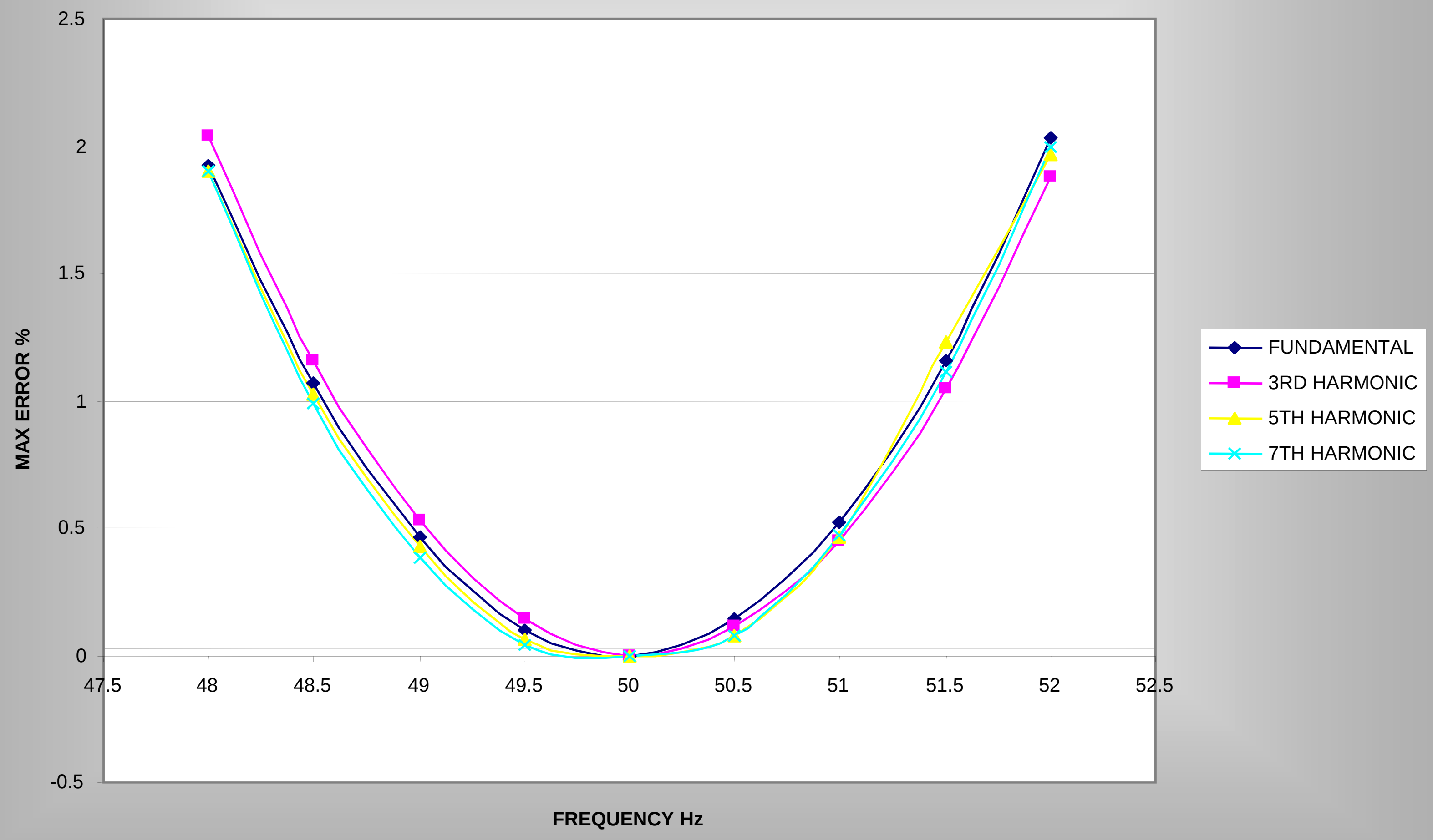
Response to a step increase of 5th harmonic component

Maximum Error in FFT Caused by Normal System Frequency Variations

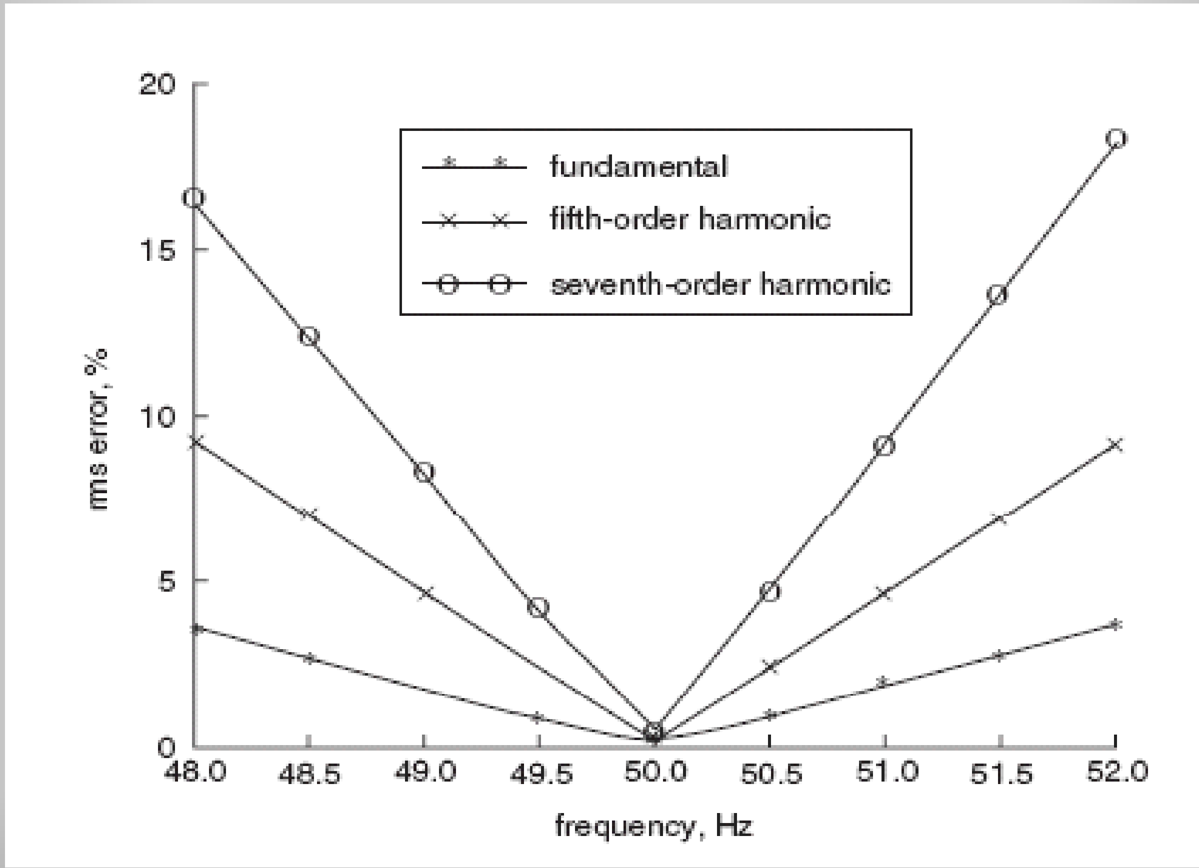
$$F(n\omega_0) = \frac{1}{T_0}\int_{t}^{t+T_0} f(t)\cdot e^{-jn\omega_0 t}\,dt$$



Maximum Error in CWT Caused by Normal System Frequency Variations



Maximum Error in ANN Technique Caused by Normal System Frequency Variations

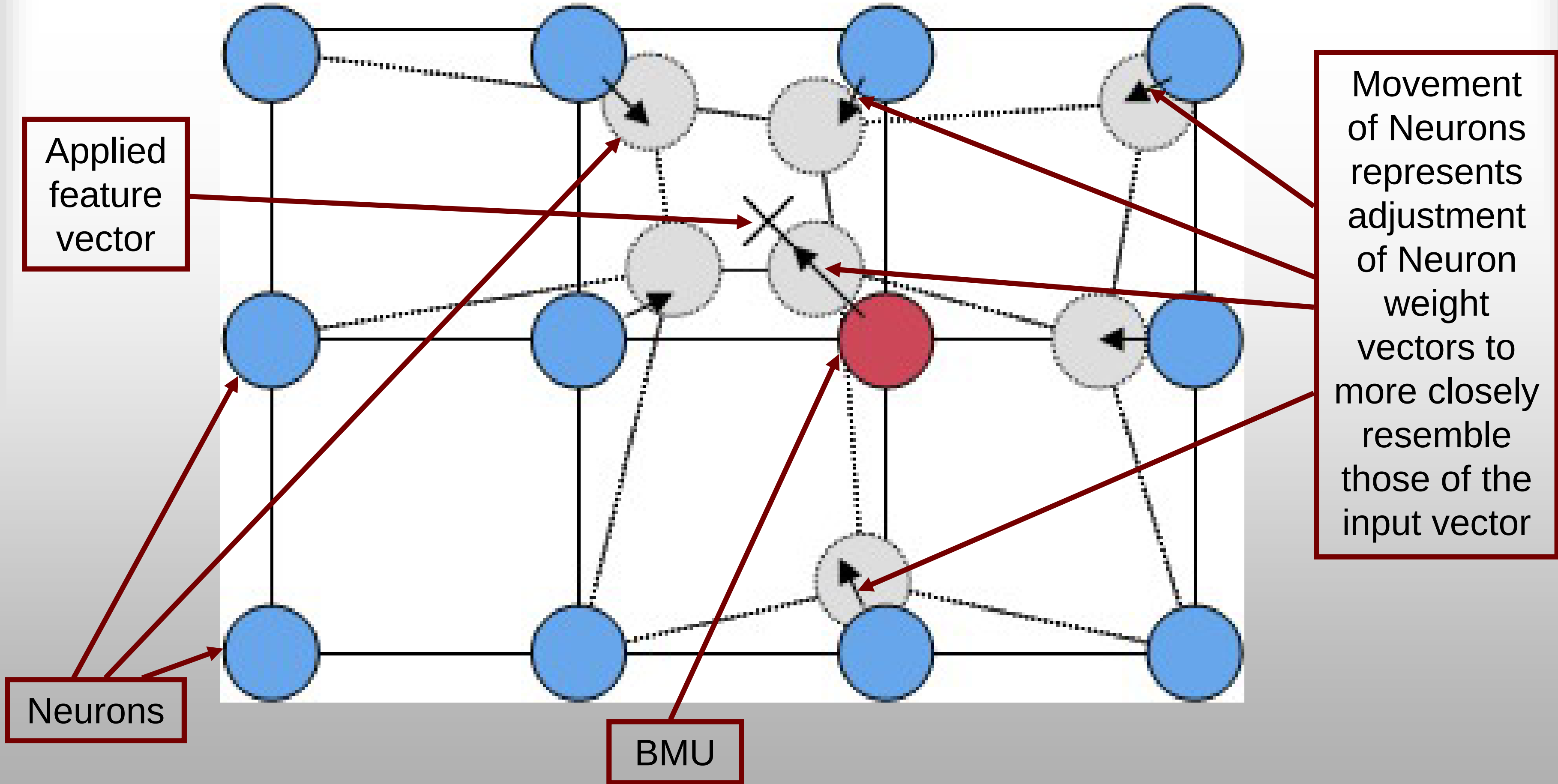


Correction for Error due to Normal System Frequency Variations

- The error could be avoided if the sampling period is adjusted digitally to make one wavelength of the adjusted fundamental signal equal to one period of the fundamental frequency (0.02 s for 50 Hz).
- Measurements, with e.g. FFT, will then give correct results as far as the effects of frequency deviation are concerned.

Source Identification using ANN

A feature vector is applied to all the neurons in the network, and its Euclidean distance to all neuron weight vectors is computed. The weights of the Best Matching Unit (BMU) and neurons close to it in the SOM lattice are adjusted towards the input vector.



Updating the winner neuron and its neighbours in a
Self Organising Map (SOM)

Architecture of the Self Organising Map

- Mapping from the input vector **X** onto two dimensional array of neurons
- Every neuron '**I**' has a parametric model vector $\mathbf{m_i}$.
- **X** is connected to all neurons via weights $\boldsymbol{w_{ij}}$.
- In the learning process, **X** is compared with every $\mathbf{m_i}$, and the location of the best match ($\mathbf{m_c}$) is:

$$\|\mathbf{x} - \mathbf{m}_c\| = \min_i \{\|\mathbf{x} - \mathbf{m}_i\|\}$$

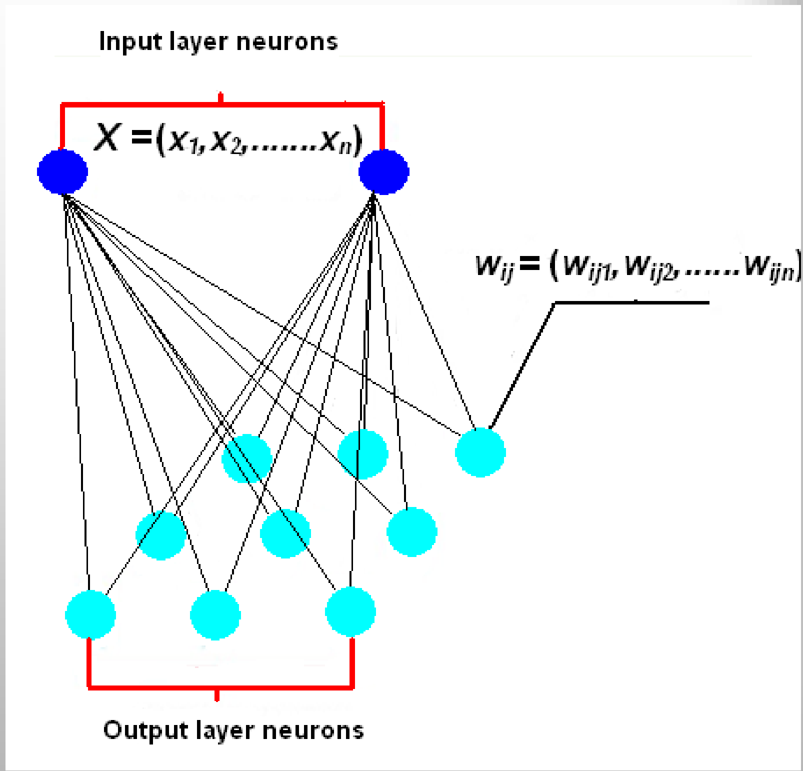
- Neurons close in the array learn from input **X** which leads to global ordering.
- The convergence limit with random initial values of $\mathbf{m_i(0)}$ is:

$$\mathbf{m}_i(\mathbf{t}+1) = \mathbf{m}_i(\mathbf{t}) + \mathbf{h}_{ci}(\mathbf{t})[\mathbf{x}(\mathbf{t}) - \mathbf{m}_i(\mathbf{t})]$$

Where **t** = 0,1,2.. is the discrete time coordinate

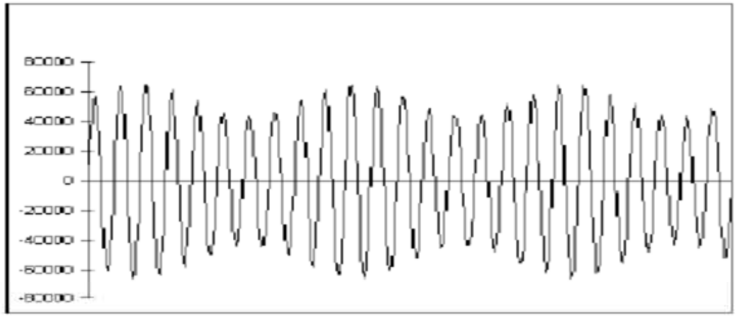
$\mathbf{h_{ci}(t)}$ is defined as the *neighbourhood function*

- The function $\mathbf{h_{ci}(t)}$ has a central role for convergence $\mathbf{h_{ci}(t)} \longrightarrow \mathbf{0}$ when $\mathbf{t} \longrightarrow \infty$.



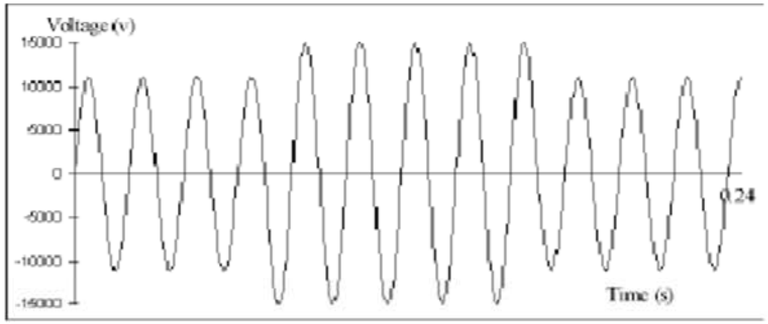
Example of Typical Disturbances used for Source Identification

Disturbances – Voltage Flicker

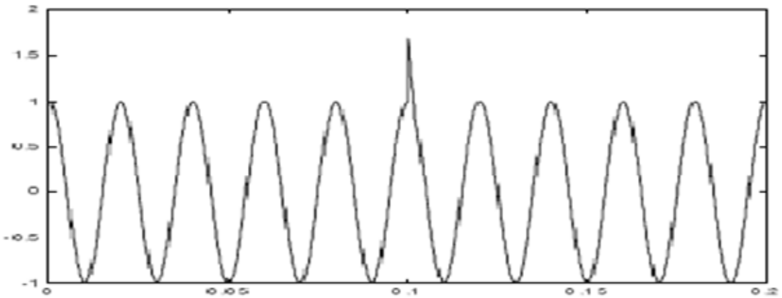


y axis V x axis time(s)

Disturbances – swell

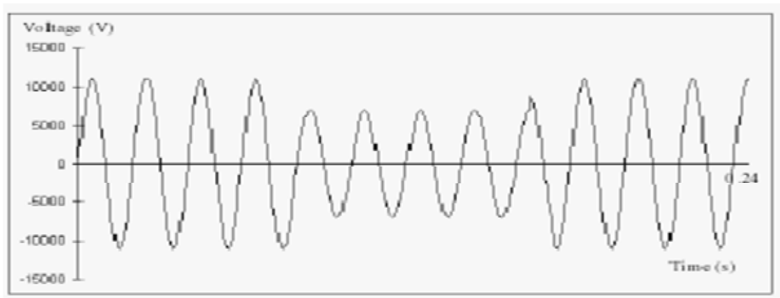


Disturbances –impulsive transient



x axis time(s) y axis Voltage (pu)

Disturbances – sag



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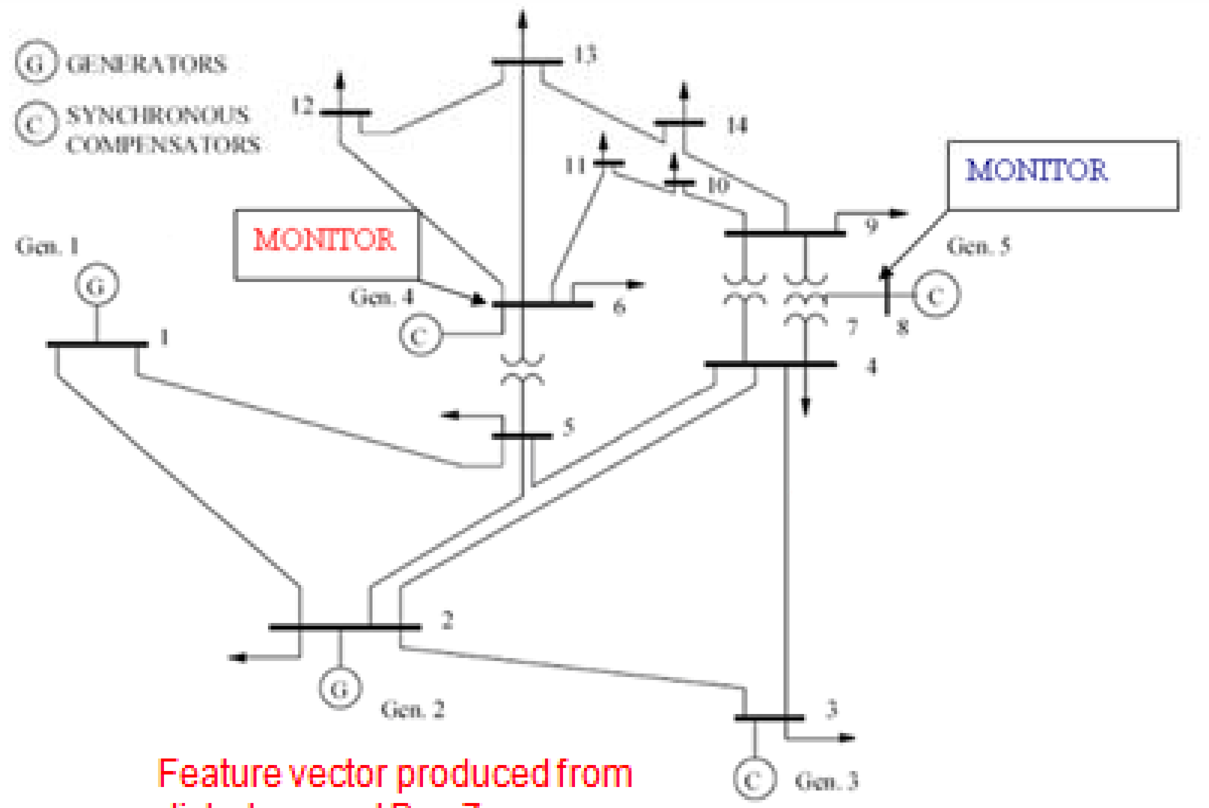
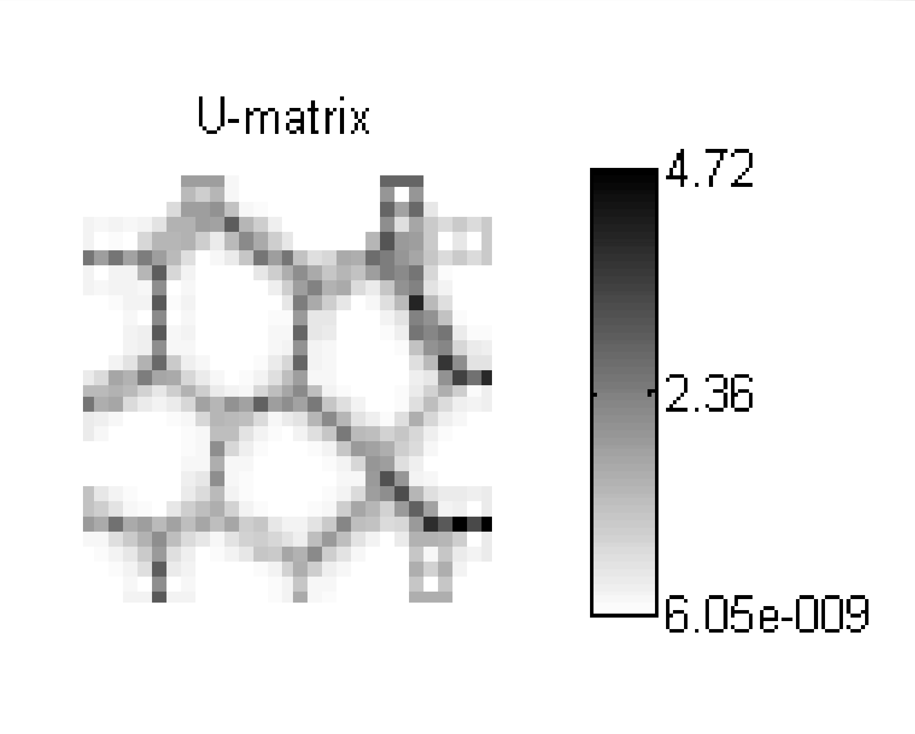
Simulated System (IEEE 14 Bus)



B6SEC	B6THIR	B6FOUR	B6FIV	B6SIX	B6SEV	B8SEC	B8THIR	B8FOUR	B8FIV	B8SIX	B8SEV	EQ1	EQ2	
2.49	.71	1.53	.75	.71	1.11	.66	.55	.81	.32	.15	.16	0	0	Bus8

The U-Matrix

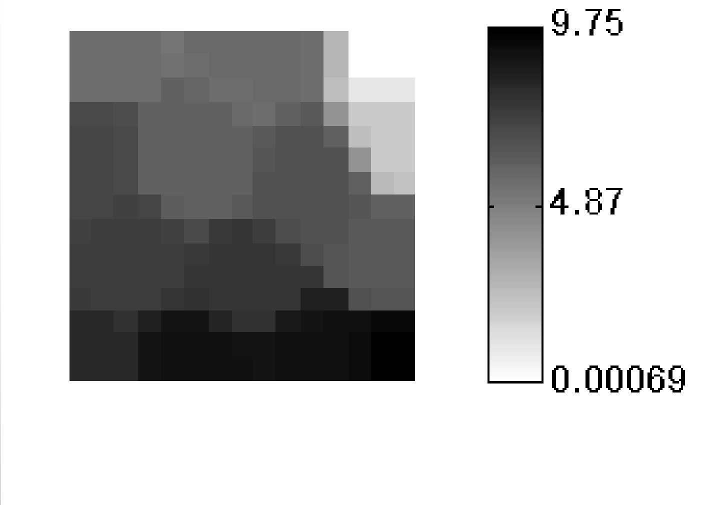
- The U-Matrix shows the organisation of the map of neurons after self training.
- After self training, the darker the colour the more the neuron weights differ from each other; light colouring shows areas of similarity – here signals from each particular source are clustered (shown white)



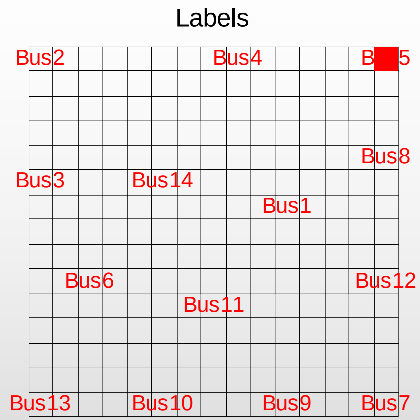
Simulation using IEEE 14 Bus System

Similarity display showing Euclidean distance between the input vector produced from a disturbance at Bus 5.

The shorter the distance the better is the match and brighter is the cluster.



Neuron Model Vectors in trained Map (U-Matrix)

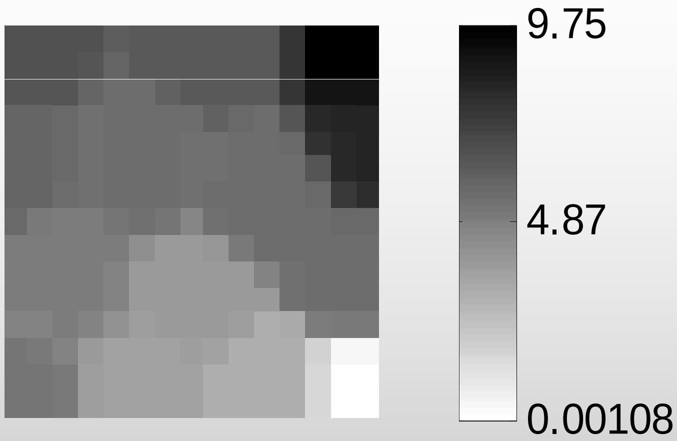


Output of ANN showing bus labels.

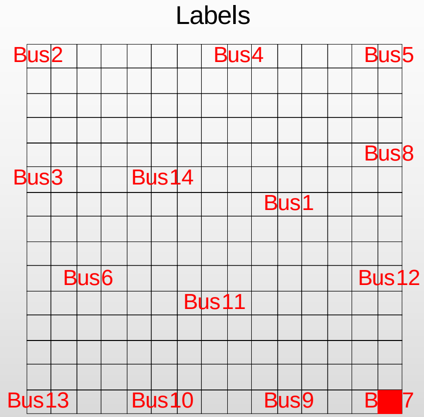
Red dot shows source of disturbance

Similarity display and output of ANN showing correct identification of a transient signal from Bus 5

Simulation using IEEE 14 Bus System



Neuron Model Vectors in trained Map (U-Matrix)

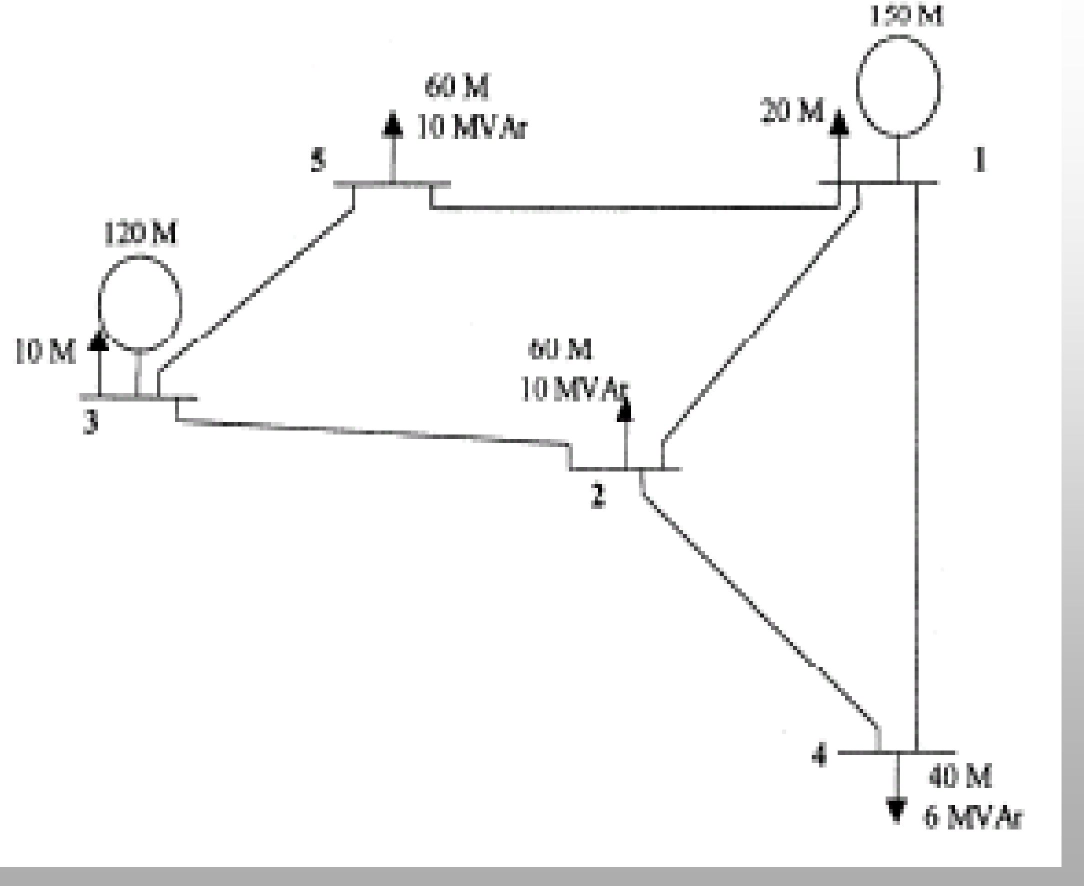


Output of ANN showing bus labels.

Red dot shows source of disturbance

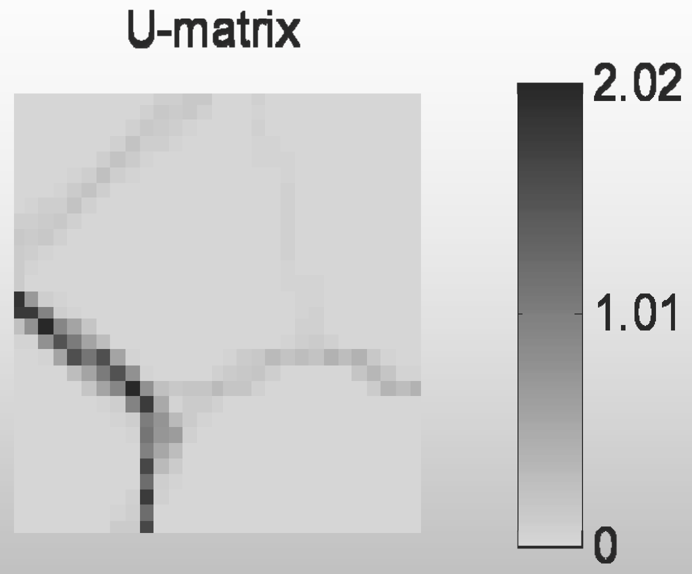
Similarity display and output of ANN showing correct identification of a transient signal from Bus 7

Experimental System Based upon Modified IEEE 6 Bus System

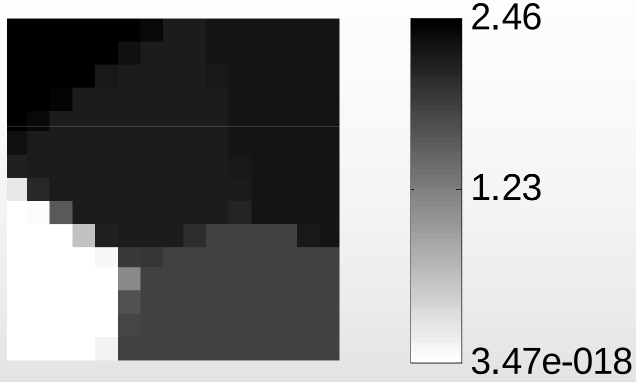


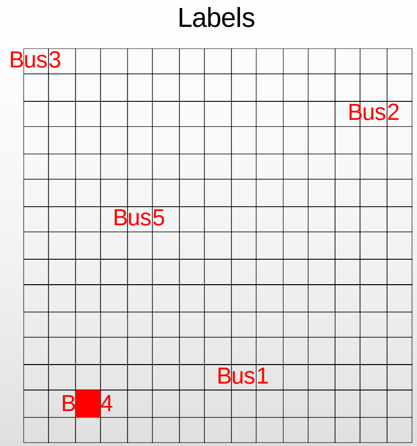
Experimental Results for the Modified IEEE 6 Bus System

- U-Matrix shows the organisation of the Map neurons after self training.
- The darker the colour the more the neuron weights differ from each other
- Light colouring shows areas of similarity – here signals from each particular source are clustered shown lighter grey



Experimental Results for the Modified IEEE 6 Bus System



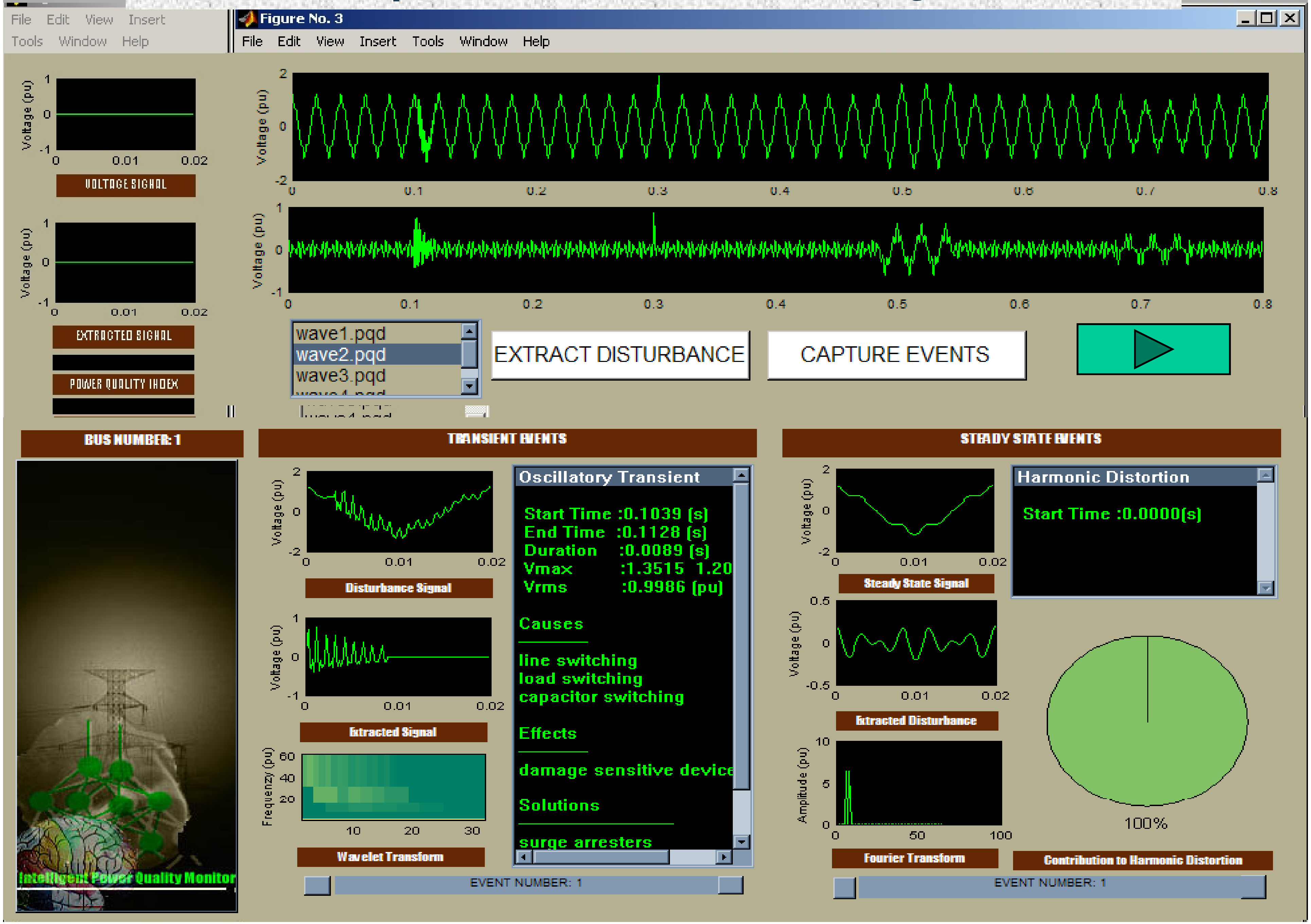


Neuron Model Vectors in trained Map (U-Matrix)

Output of ANN showing bus labels.
Red dot shows source of disturbance

Similarity display and output of ANN showing correct identification of 3rd harmonic signal from Bus 4

Graphical Interface of the IPQMS



Summary

- Power Quality monitoring is necessary in order to maintain a good quality electrical supply
- PQ monitoring and analysis equipment are becoming powerful, low cost and smaller in size.
- Most are capable of performing basic PQ monitoring and harmonics analysis.
- Portable, fixed and multipoint equipment are capable of monitoring and analysing PQ disturbances.
- Use of Digital Signal Processing (DSP) techniques in PQ monitoring and analysis results in accurate, sophisticated and powerful equipment.
- DSP based equipment is capable of maintaining accuracy in the "non-ideal environment" of power systems.

Summary

- Including Artificial Intelligence enables PQ monitoring equipment to:
  - Identify, classify and locate the source of a disturbance
  - Determine contribution levels of disturbances coming from different sources.
  - Perform long term feature analysis and learn from experience!
  - Provide methods to identify trends over a period of time and possible solutions!